In veterinary practice, the diagnosis of gait abnormalities in dogs is still primarily based on subjective observation of the gait pattern. However, the diagnostic accuracy, sensitivity, and intra- and interobserver variability of subjective gait analysis vary widely and are considered to be inferior to objective gait analysis.\textsuperscript{1-3}

Kinematic data provide objective information for veterinarians to diagnose musculoskeletal and neurological disorders and to monitor therapeutic success in dogs.\textsuperscript{4-6} Although 3-D kinematic gait analysis with systems such as VICON-Nexus (VICON Motion Systems Ltd) or Optotrak (NDI) is considered to be the gold standard for kinematic gait analysis,\textsuperscript{5,7} it is still limited to research facilities, universities, and large referral hospitals due to the high cost, time requirements, and complexity of this sophisticated instrumentation.\textsuperscript{8,9}

Several recent veterinary and human studies\textsuperscript{7,10,11} indicate that 2-D kinematic gait analysis may also adequately detect pathologic limb movements. Recently, 2-D kinematic motion analysis (KMA) has become more accessible and affordable due to the...
technological advancement of smartphone cameras, computers, and video analysis software. Kinovea (http://www.kinovea.org) is a freely available open-source software for 2-D KMA of video recordings with minimal technical effort. Kinovea allows for movement analysis of captured objects, taking the perspective between camera and captured object into account if correctly calibrated. In people, Kinovea has been employed for sports-related, gait, and ergonomic analyses. The software has been validated for range-of-motion (ROM) measurements in human physiotherapy, lower extremity gait analysis, and motion analysis of jumps and fitness exercises and as part of a low-cost clinical gait analysis system.

Throughout the last decade, Kinovea has been increasingly employed for motion analysis in numerous areas of veterinary research. In the field of canine sports medicine, the effect of surface compliance on hindlimb kinematics was studied in galloping greyhounds. The results of this Kinovea-based study of hock joint dynamics were intended to provide important information for proposing future changes in track surface composition to improve animal welfare in the racing industry. The landing kinematics of agility dogs traversing the A-frame and working dogs traversing wooden walls of varying heights have been studied using Kinovea, with the aim of using this information to reduce the risk of injury. Kinovea is suitable for aquatic motion analysis and has already been utilized to investigate the effect of life jackets on active joint ROM in swimming small-breed dogs. Another aquatic Kinovea-based study showed increased active carpal and tarsal ROM when the water flow rate was increased in Siberian Huskies swimming under countercurrent conditions. This information could improve rehabilitation and training regimes in the future. Using Kinovea, important ergonomic information has been obtained regarding the kinematic changes induced by harnesses on working dogs.

Despite all these studies, Kinovea has not yet been validated for kinematic gait and motion analysis in dogs. The objective of this study was to evaluate the accuracy of Kinovea-based 2-D kinematic gait analysis of healthy dogs walking on a treadmill in comparison to a 3-D motion analysis system. We hypothesized that Kinovea would be able to provide accurate kinematic data when recording in the sagittal plane.

**Methods**

**Animals**

Client-owned, large-breed, healthy adult dogs with no signs of lameness were recruited for this study. Written informed consent was obtained from the owners. Each dog then underwent a complete general and orthopedic examination by the first author and/or an American College of Veterinary Surgeons/European College of Veterinary Surgeons Diplomate. Dogs were weighed on a scale, and their height at withers was measured using a tape measure and spirit level. The body conditioning score was documented for each dog. Dogs with a short- to medium-length coat, a body weight more than 20 kg, and a height of more than 50 cm at withers were included in this study. The short-to-medium coat length was chosen because the markers were applied to the coat without prior shaving. Only large-breed dogs were included as all dogs were recorded at the same frame rate, and smaller dogs would have required a higher frame rate for optimum accuracy. Dogs were excluded if they showed signs of general, neurological, or orthopedic disease during the examination. Dogs unwilling to walk on the treadmill in the gait analysis laboratory were excluded from participation. The study protocol was approved by the ethics committee of the Centre for Veterinary Medicine, Ludwig-Maximilians-Universitaet, Munich, Germany (approval number: 283-13-08-2021; date of approval: January 3, 2022).

**Instrumentation**

After a period of acclimatization in the gait analysis laboratory, each dog was instrumented with a custom-made set of passive markers. The markers consisted of wooden spheres with a diameter of 10 mm, which were covered with reflective material. The markers were attached to a round piece of light-blue felt, approximately 20 mm in diameter, and attached to the fur with double-sided adhesive tape over the following palpable bone points: the external sagittal crest, the spinous processes of C3, T3, T6, T10, T13, L3, L5, and L7. Additional markers were attached at the middle of the median sacral crest, the most caudal point of the ischial tuberosity, and at the base of the tail. On the forelimbs, the markers were attached at the dorsal scapular border proximal to the scapular spine, the proximodistal center of the scapular spine, the greater tubercle, the lateral humeral epicondyle, the ulnar styloid process, and the lateral epicondyle. On the hindlimbs, the markers were attached at the most dorsal point of the ischial crest, the greater trochanter, the lateral femoral epicondyle, the lateral malleolus, and the lateral aspect of the head of the fifth metatarsal bone. Supplementary markers were placed midway between the adjacent joint markers on the brachium, antebrachium, upper thigh, and crus.

**Kinematic gait analysis**

Optical motion analysis was performed with the dogs walking on a 2-belt free-standing treadmill (dimensions: length, 135 cm; width, 80 cm) embedded in a low platform in a gait laboratory (Figure 1) instrumented with a system of 8 high-speed infrared cameras recording at 100 Hz (Vicon ver, version 2.2; VICON Motion Systems Ltd) and a digital camera (Vicon Vue; VICON Motion Systems Ltd). Simultaneously, the dogs were filmed with a smartphone (iPhone SE 2022; Apple Inc) mounted on a tripod on the left side of the dog at shoulder height at a distance of 1.50 m and a recording angle of 90°. The height of the tripod was adjusted individually for each dog to allow recording at shoulder height. The
left-hand side was chosen for exemplary analysis in order to avoid processing excessive amounts of data and to reduce data processing time. The frame rate of the recording was 60 frames per second at a resolution of 1,920 X 1,080 pixels (Figure 1).

During the acclimatization period and the recording, each dog was loosely led by the collar by 1 handler when walking on the treadmill. Positive reinforcement in the form of verbal praise or treats was used to encourage forward movement toward the leading veterinary technician or veterinary student. The treadmill speed was set individually for each dog in increments of 0.02 m/s, allowing them to walk at a relaxed, consistent pace. After an acclimatization period of 2 to 5 minutes, synchronized video recordings (duration, 2 minutes) were initiated.

**Synchronization**

A large digital alarm clock (dimensions: length, 206 mm; width, 30 mm; height, 130 mm) was positioned within the field of view of the smartphone camera and the VICON Vue digital camera on the treadmill platform.

The first 6 consecutive, even gait cycles of the left front and hindlimb, with the dog walking at an even pace in a straight line and with as little head movement as possible, were identified on the smartphone video recordings. The frame in which the left metacarpal marker was in the most cranial position was defined as the cranial turning point (frame 0). It was determined in Kinovea (version 0.9.5; http://www.kinovea.org) using the linear kinematics tool. Frame 0 was chosen as the frame with the lowest number on the y-axis, corresponding to the most cranial position of the marker (Figure 2). The time on the digital alarm clock was read off at frame 0.

The synchronous sequence in the VICON-Nexus recordings was selected based on the digital alarm clock reading to select the synchronous cranial turning point.

**Quantitative video analysis**

**Kinovea**

The carpal, elbow, shoulder, tarsal, stifle, and hip joint angles were labeled and tracked using the angle tool (Figure 3).

For correct tracking, the marker had to be positioned within the reflective sphere. Each frame was verified for correct marker tracking and manually corrected if tracking was inadequate.

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**Figure 1**—Camera setup in the gait analysis laboratory. The smartphone is mounted on a tripod at shoulder height, recording at a 90° angle relative to the shoulder joint and at a distance of 150 cm (Source: Elena Winkler).
Figure 2—Linear kinematics of the horizontal position of the metacarpal joint marker. For synchronization, frame 0 was chosen as the frame with the lowest number on the y-axis, corresponding to the most cranial position of the marker.

Figure 3—Treadmill-based kinematic motion analysis of the left shoulder, elbow, carpal, hip, stifle, and tarsal joint utilizing Kinovea.
A second-order Butterworth filter was applied to the marker coordinates.

Three-dimensional motion analysis
The recorded markers were assigned to their corresponding anatomical landmarks within a calibrated anatomical axis system to digitally reconstruct stick figures using data capture software (VICON-Nexus, version 2.12.1; VICON Motion Systems Ltd). For the kinematic analysis, joint angle progression was assessed using the software VICON ProCalc, version 1.6 (VICON Motion Systems Ltd). A fourth-order (zero lag) Butterworth filter was applied to the marker coordinates. Maximum flexion and extension angles and ROM were calculated for each joint.

The angle curve plots underwent visual quality control by checking the graphs for plausibility of marker tracking in VICON-Nexus and Kinovea. If the curve indicated a loss of correct marker tracking, the analysis was repeated in the respective program. All time-angle curves were normalized to a gait cycle of 100% and divided into 10% increments.

Statistical analysis
The data were analyzed in the statistical program R using the packages lme4, emmeans, robustlmm, and performance. In order to decide whether a linear or a robust linear mixed-effects model was better suited to the data for each parameter, the performance of a linear and a robust linear mixed-effects model was evaluated using 6 main performance quality indicators: the Akaike information criterion, Bayesian information criterion, conditional coefficient of determination $R^2$, marginal coefficient of determination $R^2$, intraclass correlation coefficient, and root mean square error. The model showing the best combination of predictive (Akaike information criterion and Bayesian information criterion) and fitting (explanatory, $R^2$, intraclass correlation coefficient, and root mean square error) power was applied. All differences between particular groups were assessed after model fitting by the estimated marginal means (R package, emmeans) with Tukey $P$ value correction for multiple comparisons. Shoulder, elbow, carpal, hip, stifle, and tarsal joint angles, joint angle velocities, and maximum flexion, extension, and ROM were explored as response variables via the interaction between the methods Kinovea and 3-D motion analysis and the percentage of the gait cycle. Each individual dog was used as a random effect on the intercept. The repeated measure for the individual animals were collected for each of both methods and for 6 gait cycles. The significance level was adjusted to the sample size using the Good 1988 function. Therefore, differences were considered significant at $P < .003$.

Results
Animals
Twenty-one males (n = 8 intact; n = 13 neutered) and 13 females (n = 8 intact; n = 5 spayed) were included. The mean body weight was 29.7 ± 5.2 kg, and the mean body condition score was 4.4 ± 0.6. The mean height at the withers was 61.1 ± 5.7 cm. Breeds represented were Labrador Retriever (n = 11), mixed breeds (n = 9), European Sled Dog (n = 3), Dalmatian (n = 2), Weimariner (n = 2), Beauceron (n = 2), Golden Doodle (n = 1), Foxhound-Boxer-Ingelheim Labrador Retriever (n = 1), Saluki (n = 1), Old German Shepherd (n = 1), and Dutch Shepherd (n = 1). The mean age was 4.4 ± 2.5 years.

Minimum, maximum, and ROM measurements
The estimated difference between the 2 systems was less than 3° for maximum joint flexion, extension, and ROM of all joints, except for the carpus and hip. The largest difference was observed with ≤ 9.0° for maximum carpal extension and ≤ 6.4° for maximum hip flexion.

The estimated difference between Kinovea and 3-D motion analysis was less than 2.0° for maximum shoulder flexion and extension. Shoulder ROM differed by up to 3.1° between the 2 systems. Maximum elbow flexion and extension differed by less than 1.5°. Elbow ROM differed by up to 2.3° between Kinovea and 3-D motion analysis. The highest estimated differences were observed for the carpal joint. Although maximum flexion only differed by up to 2.3°, maximum extension differed by up to 9.0°. Carpal ROM differed by up to 11.0° between Kinovea and 3-D motion analysis.

For the hindlimb, one of the largest estimated differences was observed for maximum hip flexion, differing by up to 6.4° between 3-D motion analysis and Kinovea. Despite maximum hip extension differing by only up to 1.2°, hip ROM differed by up to 5.6° between Kinovea and 3-D motion analysis. Differences in stifte and tarsal maximum extension, flexion, and ROM remained below 3°.

Joint angles
Forelimb joints
For most increments of the gait cycle, joint angle curves did not differ significantly between Kinovea and 3-D motion analysis. In 2 of 10 increments, carpal joint angles differed significantly between the systems. In 4 of 10 increments, elbow and shoulder joint angles differed significantly between the systems. Differences between 2-D and 3-D motion analysis were less than 1.5° for the shoulder and elbow joints and less than 5° for the carpal joint. The greatest estimated difference was observed in the 80% to 90% increment, with 4.1° for the carpal joint (Figure 4).

Hindlimb joints
For most increments of the gait cycle, the joint angle curves differed significantly between Kinovea and 3-D motion analysis. The estimated differences between the joint angle curves of the 2 systems were less than 5° for all increments of the hindlimb joints, except for the hip joint, with an estimated difference of 5.4° for the 90% to 100% increment.
Joint angle velocities

Forelimb joints

For less than half of the increments of the gait cycle, shoulder and elbow joint angle velocity curves did not differ significantly between Kinovea and 3-D motion analysis. In 8 of 10 increments, carpal joint angle velocity differed significantly between the systems. Joint angle velocity differed by less than 50°/s for the shoulder and elbow joints and by less than 210°/s for the carpal joint between 2-D and 3-D motion analysis. The greatest estimated joint angle velocity difference between the systems was observed in the 60% to 70% increment, with 209.3°/s for the carpal joint (Figure 5).

Hindlimb joints

For greater than or equal to 50% of the increments of the gait cycle, joint angle velocity curves differed significantly between Kinovea and 3-D motion analysis.

Figure 4—Comparison of joint angles between Kinovea and 3-D motion analysis. Increments marked with * indicate gait cycle increments with joint angles differing significantly between the 2 systems (significance level set to $P < .003$).
analysis. For all increments of the gait cycle, the estimated joint angle velocity differences between the systems were less than 40°/s for all joints.

**Discussion**

The aim of this study was to evaluate the accuracy of Kinovea as a low-cost 2-D alternative to 3-D kinematic gait analysis in healthy dogs walking on a treadmill. We hypothesized that Kinovea would be able to provide accurate kinematic data when recorded in the sagittal plane. This hypothesis was partially confirmed as Kinovea provided accurate kinematic data for all forelimb joints except for the carpal joint.

Although joint angles and joint angle velocities differed significantly between Kinovea and 3-D motion analysis, this may have been partly due to the high number of observations of the study and was not necessarily associated with clinically significant
differences. As postulated by McGinley et al.\textsuperscript{34} in a systematic review on the reliability of human 3-D kinematic gait measurements, we considered differences of less than 2° to be acceptable and less than 5° to be reasonable for the purpose of this study. This is in line with previous veterinary studies\textsuperscript{35} showing comparatively high variation in kinematic measures over multiple days of examination. Thus, compared to 3-D kinematic analysis, Kinovea-based gait waveform analysis provided acceptable carpal, elbow, and shoulder joint angle measurements during all gait cycle increments, except for the carpal joint angle measured during 1 of the 10 gait cycle increments. Accordingly, Kinovea-based joint angles were considered acceptable or reasonable for all increments of the hindlimb gait cycle, except for 1 increment of the coxofemoral gait cycle. In summary, the estimated difference in maximum joint flexion, extension, and ROM was considered acceptable or reasonable for all joints except for the carpus and hip.

The joint angle velocity curves showed less systematic error than the joint angle curves, probably because the joint angle velocity curves are the mathematical derivative of the joint angle curves, thus removing systematic offsets along the y-axis (Figure 5).

In our study, we observed larger differences between Kinovea and 3-D motion analysis for the hindlimb joints compared to the forelimb joints. The larger differences for the hindlimb kinematics are explainable by perspective distortion as the hip, stifle, and tarsal joints were not recorded at a 90° angle in our smartphone setup.\textsuperscript{56} Consequently, the distance between the hindlimb joints and the optical axis of the smartphone camera was larger compared to the forelimb joints. Two-dimensional video analysis experiences perspective distortion due to the change in magnification with depth as uniplanar recording does not allow for depth measurement. Thus, a more distant object will appear smaller upon video analysis than the same object closer to the camera. For the same reason, different markers on a dog may appear to move at different speeds. As markers are attached to a curved body surface, markers moving with constant velocity may appear to accelerate falsely when analyzed with 2-D motion analysis.\textsuperscript{36,57} In order to reduce perspective distortion in future studies, it is recommended to adjust the camera setup to position the examined joint in the center of the optical axis.

The largest deviations were observed for the 80% to 90% increment during the carpal gait cycle and for the 90% to 100% increment during the hip gait cycle. This finding is most probably associated with optical out-of-plane motion causing these deviations in 2-D gait analysis.\textsuperscript{5,36} When an object moves in and out of the calibrated plane, this may lead to joint angle discrepancies due to differing distances of 1 and the same marker in relation to the optical lens. This is particularly notable during carpal and hip kinematics as the carpus supinates at maximum flexion. The hip joint shifts out of plane at the maximum flexion as the pelvis shifts axially during the stand phase of the contralateral hindlimb.\textsuperscript{58,59}

Joints move in 3 planes and 6 degrees of freedom.\textsuperscript{50} Differences in joint kinematics are inherent in the nature of the systems, with VICON-Nexus being a 3-D motion analysis capable of capturing motion in 3 planes and Kinovea being a 2-D motion analysis system recording in 1 plane.\textsuperscript{40,41} A previous comparative study\textsuperscript{7} on 6 dogs walking on a walkway showed good agreement between 2-D and 3-D kinematic gait analysis systems for coxofemoral, stifle, and tarsal kinematics. In this study, significant gait-cycle-dependent, joint-specific angular differences could not be observed between the 2 systems. However, this may have been due to the small sample size. Consistent with this study, we observed good agreement between 2-D Kinovea and 3-D motion analysis. However, in contrast to this study, we were able to demonstrate joint-specific differences between the systems, dependent on the gait cycle phase, most probably due to the larger sample size in our study. Other veterinary studies comparing 2-D and 3-D in a previous comparative study\textsuperscript{7} observed differences between the 2 methods that vary greatly between the different joints and the different phases of the gait cycle. For example, Diogo et al.\textsuperscript{42} reported differences of up to 12° in the swing phase of the metatarsophalangeal joint in sheep.

Kinovea and the 3-D motion analysis system recorded at different frequencies, with Kinovea recording at 60 Hz and the 3-D motion analysis system recording at 100 Hz. As motion capture systems with lower sampling rates are inherently more likely to miss high-speed events, this could have resulted in a systematic underestimation of Kinovea-based joint angles during maximum extension and overestimation of Kinovea-based joint angles during maximum flexion.\textsuperscript{7} In spite of this, this was not observed in our data, indicating that a sampling rate of 60 frames per second is sufficient for capturing maximum flexion and extension for medium- to large-breed dogs at walking speed on a treadmill. This may have been aided by the fact that both systems used Butterworth filters as frequency filters, which smoothed the respective data sets.\textsuperscript{45}

As other authors\textsuperscript{44} have previously proposed, our study shows that 2-D joint angle measurements are generally more accurate when recorded in the sagittal plane and at a 90° angle relative to the analyzed joint markers. In previous veterinary Kinovea-based kinematic studies,\textsuperscript{20,21,23–25} authors frequently did not describe the exact camera setup and did not include the camera angle relative to the examined joints. This may affect the accuracy and replicability of the joint angle measurements and consequently the conclusions drawn from the study results. For instance, in a previous Kinovea-based study,\textsuperscript{21} investigating the effect of scale height in working trials, the dogs were filmed during the landing phase after traversing an obstacle. The camera position was described as "lateral placement to the scale," but the angle of the camera relative to the joints (shoulder and carpus) analyzed at the point of landing was not defined. Moreover, it was not clarified where the dogs landed relative to the camera when the scale height was altered. This could potentially lead to deviating...
Kinovea-based joint angles, with a systematic error differing depending on the individual scale height. In future studies, ideally the camera angle should be adjusted according to the landing position to allow capture of the joints of interest at a 90° angle relative to the analyzed joints to eliminate this confounder. This study had several limitations. First, Kinovea and the 3-D motion analysis system each have different requirements for ideal recording conditions. Thus, to allow a direct comparison of the 2 methods, we had to compromise in terms of lighting conditions, marker color, and recording location.

Although Kinovea performs better in bright lighting conditions, the high-speed infrared cameras of the 3-D motion analysis system generally struggle with excessive lighting, resulting in the presence of numerous ghost markers. Furthermore, similar to previous studies, we observed that poor tracking was a problem when using Kinovea, specifically against a nonhomogeneous background. The recordings in our study were performed in a high-level 3-D gait analysis laboratory. The presence of multiple cameras, cables, and equipment in the background of the recording area made Kinovea-based marker tracking more challenging. Thus, to use light-blue markers was based on initial tests indicating their effectiveness in dark-coated and Dalmatian dogs for Kinovea-based marker tracking. Furthermore, the light-blue markers provided sufficient contrast with the retroreflective markers needed for the 3-D system. However, in dogs with light-colored coats, the use of light-blue markers often resulted in inadequate tracking in Kinovea due to insufficient contrast. Consequently, for the purpose of our comparative study, manual correction of marker tracking was frequently required, prolonging the duration of Kinovea-based kinematic analysis, often to 2 to 3 hours per dog. Thus, to optimize tracking in future studies, markers should be chosen individually to provide maximum contrast for each dog (for example, black markers on a white dog and white markers on black dog). Recording with a plain, high-contrast background with bright lighting is recommended for Kinovea-based canine studies to further minimize the need for manual marker correction.

Second, our study population consisted of clinically healthy, large-breed dogs with short to medium-long coats. It was beyond the scope of our study to evaluate the accuracy of Kinovea-based kinematic measurements in small-breed dogs. Further research is needed to determine the influence of dog size as this could affect both the required recording frame rate, as small dogs tend to move their limbs faster, and the required resolution, as the distances between joint markers are comparatively smaller. Moreover, further investigation is needed to determine if Kinovea analysis on a small- or miniature-breed dog would be associated with reduced perspective distortion, as the entire dog would be closer to the optical axis of the camera with the correct set-up.

Third, our data were only analyzed once by 1 single Kinovea and VICON-Nexus-trained observer. For the purpose of this comparative study, intra- and interobserver variability were not determined for either system. Due to the comparative nature of the study with markers not ideally suited for each individual system, manual marker correction was repeatedly required for Kinovea-based measurements. This may result in observer-specific variability. Further studies with better-suited markers are required to determine intra- and interobserver variability for Kinovea-based canine kinematic gait analysis.

In conclusion, the present study shows that Kinovea can provide accurate kinematic data for joints recorded at a 90° angle, with the exception of the carpus and the hip joint. In clinical or research settings where 3-D kinematic gait analysis is not feasible or available, Kinovea provides a cost-effective and user-friendly alternative to 3-D kinematic gait analysis.

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ORCID

M.A. Mille https://orcid.org/0000-0001-9222-9141

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