Accuracy of asymmetry indices of ground reaction forces for diagnosis of hind limb lameness in dogs

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Objective—To determine the accuracy of asymmetry indices of ground reaction forces (GRF) for diagnosis of hind limb lameness in dogs.

Animals—36 healthy dogs and 13 dogs with naturally acquired cranial cruciate ligament rupture or hip dysplasia.

Procedures—Lameness for affected dogs ranged from not detectable to minor and constant. While dogs trotted on an instrumented treadmill, GRF variables were recorded and analyzed with asymmetry indices. Each index was tested for its ability to discriminate between healthy and affected dogs. Combinations of several indices were also assessed.

Results—Vertical force variables had better accuracy than craniocaudal force variables. Peak vertical force was the most accurate variable. Partial asymmetry during trotting was detected in healthy dogs. A multivariate approach that used peak vertical force and maximal rising slope yielded the optimum combination to distinguish between healthy and affected dogs. In addition, sensitivity of 92% or specificity of 95% may be achieved with 2 cutoff values while simultaneously maintaining specificity or sensitivity, respectively, at > 85%.

Conclusions and Clinical Relevance—Asymmetry indices of GRFs were accurate for detection of hind limb lameness in dogs. This is particularly relevant for study designs in which only a single gait evaluation is possible. (*Am J Vet Res* 2007;68:1089–1094)

Assessment of surgical outcome is essential for development of new procedures and comparison of surgical techniques. Force platform analysis has been commonly used because it provides a noninvasive quantitative assessment of gait.[1-3] Return to normal locomotion after cranial cruciate ligament repair,[4-8] hip replacement,[9,10] elbow joint surgery,[11,12] and shoulder[13] surgery has been evaluated. Despite the accuracy of force platforms, most studies of value are based on the comparison of data obtained before and after surgery.

In quadrupeds, locomotion can be described as a symmetric or an asymmetric gait. Trot is a symmetric gait in which the movements during 1 stride have the diagonal limbs in support followed by the other 2 limbs in support.[14] Because the 2 sides mirror each other, symmetry coefficients can be calculated to estimate the similarity of the 2 sides' movements. Conversely, asymmetry coefficients assess any deviation from this ideal situation.

Symmetry has been examined in healthy dogs during trotting. No significant difference was detected between the 2 sides,[15-17] but none of the dogs had perfect right-to-left symmetry as measured by use of kinetic data.[15] Symmetry alteration[18,19] and the force redistribution pattern[20-23] have been investigated during induced lameness in dogs and horses. The load decrease in the injured limb and the compensatory load increase in the contralateral limb are becoming clearer. However, no comparison of symmetry between healthy and lame dogs has been attempted. Features of healthy locomotor function as evaluated by use of symmetry assessment have yet to be studied in great detail. Kinetic studies based on single-stride force plate data may be insufficient to assess gait symmetry.[15] Simultaneous analysis of consecutive strides is required.

The purpose of the study reported here was to compare the symmetry of kinetic data generated by healthy and lame dogs trotting on a treadmill. Our hypothesis was that asymmetry would be recorded for healthy dogs, but that a threshold could be determined to distinguish healthy from lame dogs.

Abbreviations

GRF	Ground reaction force
Fz	Vertical component of the ground reaction force
Fy	Cranial-caudal component of the ground reaction force
ROC	Receiver-operating characteristic
AUC	Area under the curve

Materials and Methods

Dogs—Thirty-six healthy client-owned dogs admitted to the National Veterinary School of Alfort for gait analysis between April 2004 and December 2005 were selected for use in the study. Inclusion in the study

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required that the dogs had no history of orthopedic disease and were judged to be healthy on the basis of results of physical and orthopedic examinations.

Thirteen client-owned dogs referred to the university during the same period were deemed candidates for the study. Criteria for inclusion included diagnosis of naturally acquired hind limb problems (hip dysplasia with osteoarthritis or unilateral complete cranial cruciate ligament rupture) by use of orthopedic examinations and radiography; no use of anti-inflammatory medication for 7 days prior to examination; and no obvious or marked lameness with or without weight bearing. Data reported and analyzed here were part of a larger study of postsurgical return to function; an institutional animal care and use committee approved the study, and signed owner consent was obtained. For dogs with hip dysplasia, radiographic examinations confirmed osteoarthritis in 1 or both hip joints. When both hips were affected, 1 hip joint was more severely affected by osteoarthritis, as determined on the basis of the Orthopedic Foundation for Animals classification. For dogs with cranial cruciate ligament rupture, complete rupture was confirmed during subsequent surgical inspection (usually 7 days after diagnosis but no more than 14 days at the latest) when the dog was treated. Gait abnormalities were evaluated for each dog during trotting and scored as no detectable lameness (grade 0), minor and intermittent lameness (grade 1), or minor and constant lameness (grade 2).

Gait analysis—An instrumented single-belt treadmill[a] that provided a velocity range of 0 to 7 m/s (precision, 0.028 m/s) was used. A control system enabled the belt velocity to be displayed in real time. Four force sensors situated directly on the ground under the treadmill enabled computer-assisted analysis of components of the GRF. Recorded force values were adjusted on the basis of body weight.

Each dog was habituated to treadmill locomotion prior to kinetic analysis in accordance with a method described elsewhere.[24] The GRF was recorded[b] at 500 Hz/channel for 10 seconds during trotting. The analysis velocity was chosen for each dog in a range of 2.0 to 2.8 m/s to ensure that the dog trotted. This velocity was set with a precision of 0.06 m/s. Each dog trotted on a single platform during the analysis.

Recorded data—For each step, mean and maximal rising slopes, mean and maximal falling slopes, peak, impulse, stance time, and ratio of the time to peak to the stance time were used for the Fz. Braking peak, braking impulse, propulsion peak, and propulsion impulse were used for the Fy. Mean and maximal rising slopes and mean and maximal falling slopes were calculated for the propulsion phase. No slopes were calculated for the braking phase because of the large amplitude of the impact peak.

Mean rising slope was defined as the slope of the straight line that connected the beginning of the stance phase to the peak. Maximal rising slope was determined as the maximum value among all loading rates calculated at each data point.[25] Conversely, mean falling slope was defined as the slope of the straight line that connected the peak to the end of the stance phase. Maximal falling slope was determined as the maximum value (as an absolute) among all unloading rates calculated at each data point.

The asymmetry index for each gait variable for each dog was calculated by use of the following equation[15]:

$$(|X_R - X_L|/[|X_R + X_L| \times 0.5]) \times 100$$

where X_R is the mean of a given gait variable for right footfalls during a 10-second recording and X_L is the mean of a given gait variable for left footfalls during a 10-second recording.

Data analysis—The ROC curve analysis was used to assess diagnostic properties of each asymmetry index.[c] An ROC curve represents the relationship between the true-positive rate (the probability of classifying a lame dog as lame [ie, sensitivity]) and the false-positive rate (the probability of classifying a nonlame dog as lame [ie, 1 – specificity]) for each possible cutoff value.[26] This procedure is commonly used to establish the performance of medical tests.[27-29] The closer the curve is to the upper left corner of the graph, the higher the discriminatory power of the diagnostic test.

The AUC is a global summary statistic of diagnostic accuracy that makes it possible to compare several test variables; it was calculated by use of the Wilcoxon-Mann-Whitney test. The AUC makes it possible to distinguish highly accurate (0.9 < AUC < 1), moderately accurate (0.7 < AUC ≤ 0.9), less accurate (0.5 < AUC ≤ 0.7), and noninformative (AUC ≤ 0.5) tests.[27] Pearson correlation coefficients were calculated between the highest accurate variables.

Table 1—The AUC for the ROC curve for Fz, Fy, and the optimum combination of forces in 36 nonlame and 13 lame dogs.

Variable		AUC	Classification
Fz	Peak Fz	0.92[a,b]	Highly accurate
	IFz	0.80[c]	Moderately accurate
	MeRS	0.68[c]	Less accurate
	MeFS	0.71[c]	Moderately accurate
	MaRS	0.81[b,c]	Moderately accurate
	MaFS	0.70[c]	Less accurate
	Stc	0.71[c]	Moderately accurate
	Tz	0.43[d]	Noninformative
Fy	Peak Fyp	0.48[c,d]	Noninformative
	Peak Fyb	0.46[c,d]	Noninformative
	IFyp	0.43[d]	Noninformative
	IFyb	0.47[c,d]	Noninformative
	MeRSy	0.50[c,d]	Noninformative
	MeFSy	0.61[c,d]	Less accurate
	MaRSy	0.53[c,d]	Less accurate
	MaFSy	0.47[c,d]	Noninformative
	Optimum	0.95[a]	Highly accurate

The optimum combination was peak Fz and maximum rising slope (MaRS).

[a-d]Values with different superscript letters differ significantly (*P* < 0.05).

IFz = Vertical impulse. MeRS = Mean rising slope. MeFS = Mean falling slope. MaFS = Maximal falling slope. Stc = Stance time. Tz = Ratio of the time to peak to the stance time. Peak Fyp = Propulsion peak. Peak Fyb = Braking peak. IFyp = Propulsion impulse. IFyb = Braking impulse. MeRSy = Mean rising slope of the propulsion phase. MeFSy = Mean falling slope of the propulsion phase. MaRSy = Maximal rising slope of the propulsion phase. MaFSy = Maximal falling slope of the propulsion phase.

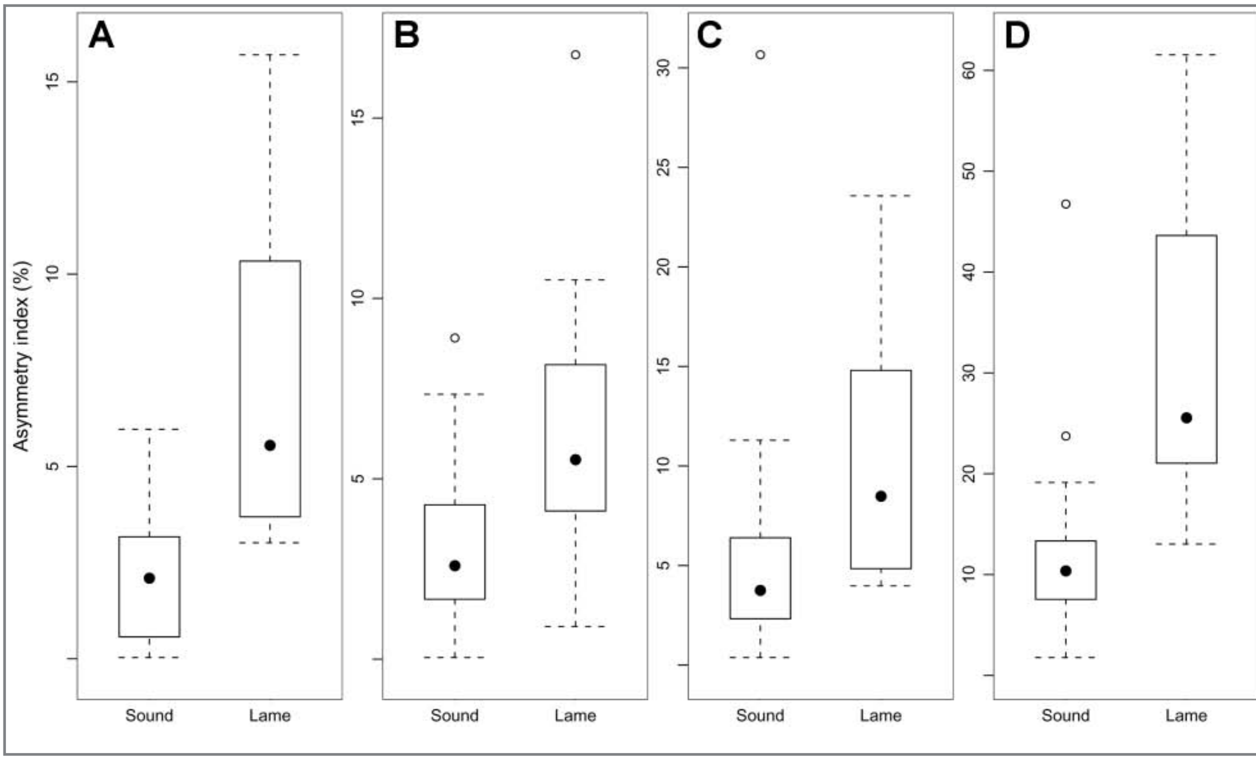

Figure 1—Box-and-whisker plots of asymmetry indices for the peak Fz (A), vertical impulse (B), maximal rising slope (C), and optimum combination of indices (D) in 36 nonlame dogs (Sound) and 13 lame dogs. Boxes represent the interquartile range, black circles represent the median, whiskers represent the maximum and minimum values, and white circles represent outliers.

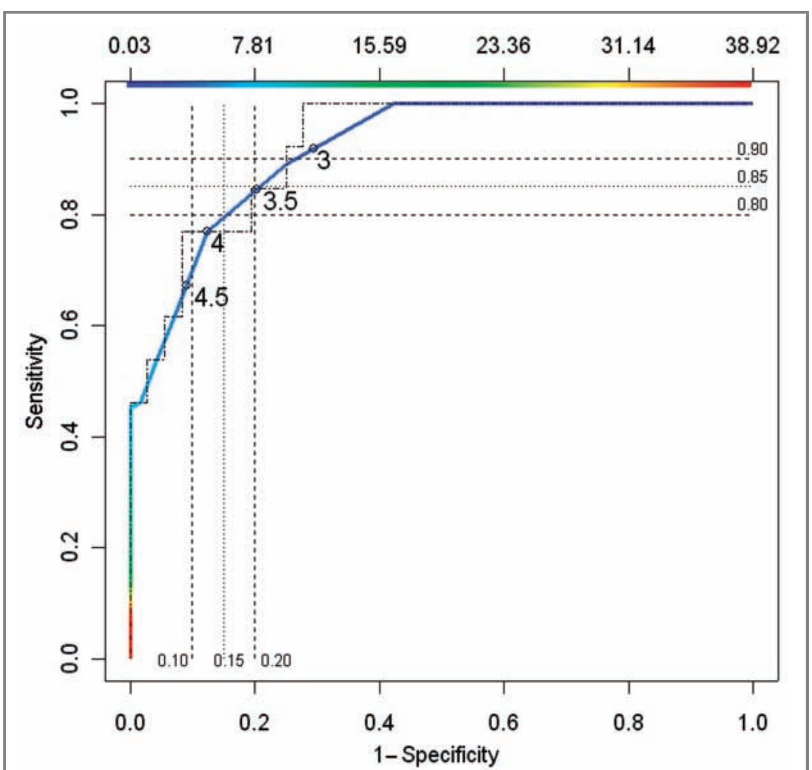

Figure 2—Receiver-operating characteristic curve of the asymmetry index for peak Fz in 36 nonlame and 13 lame dogs. The smoothed ROC curve is of various colors in accordance with the cutoff value, whereas the unsmoothed ROC curve is indicated by the dashed-and-dotted black line. Major relevant cutoff values are indicated for the curves (dashed or dotted lines).

When highly accurate variables were identified, several cutoff values were determined on the basis of the ROC curve. Each cutoff value was an asymmetry index to distinguish between lame and nonlame dogs and was linked to the combination of the sensitivity and the specificity of the test.

Results

Healthy dogs (14 males and 22 females) weighed from 13 to 52 kg (median, 28.5 kg) and were 1 to 11 years old (median, 4 years). Lame dogs (8 males and 5 females) weighed from 27 to 52 kg (median, 35.7 kg) and were 1 to 11 years old (median, 6 years). Nine dogs had hip dysplasia (6 had grade 0 lameness, 2 had grade 1 lameness, and 1 had grade 2 lameness). Four dogs had cranial cruciate ligament rupture (1 had grade 1 lameness, and 3 had grade 2 lameness).

All asymmetry indices were analyzed in accordance with the ROC procedure. The Fz variables had greater AUC than the Fy variables. The AUC calculated with the Fz variables ranged from 0.43 to 0.92 (median, 0.71), whereas AUC calculated with the Fy variables ranged from 0.43 to 0.61 (median, 0.47 [**Table 1**]). Peak Fz,

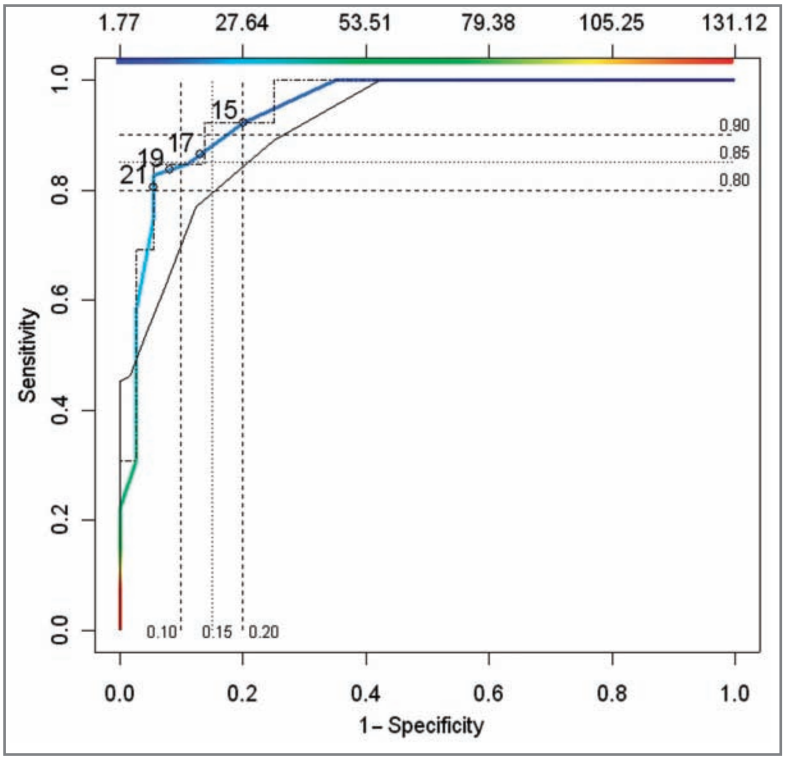

Figure 3—Receiver-operating characteristic curve of the asymmetry index for the optimum combination of indices in 36 nonlame and 13 lame dogs. The smoothed ROC curve is of various colors in accordance with the cutoff value, whereas the unsmoothed ROC curve is indicated by the dashed-and-dotted black line. The ROC curve calculated with the asymmetry index for peak Fz is indicated (solid black line). Notice the improvement for use of the optimum combination over use of peak Fz. *See* Figure 2 for remainder of key.

maximal rising slope, and vertical impulse had the highest AUC scores (0.92, 0.81, and 0.80, respectively). Pearson correlation coefficients were 0.90 between peak Fz and vertical impulse and 0.35 between peak Fz and maximal rising slope. Furthermore, overlaps between nonlame and lame dogs were found in data distribution for the peak Fz, vertical impulse, and maximal rising slope **(Figure 1)**.

The AUC score for the peak Fz was significantly different from all of the other AUC scores, except for maximal rising slope. Peak Fz was the only variable to be considered highly accurate. A cutoff value of 3.2% provided sensitivity of 92% and specificity of 75%, whereas a cutoff value of 3.5% provided sensitivity of 85% and specificity of 80%, and a cutoff value of 4% provided sensitivity of 77% and specificity of 86% **(Figure 2)**.

The optimum combination of the best 2 AUCs (peak Fz and maximal rising slope) was found by use of a trial-and-error optimization algorithm. This combination was 3 × I(PFz) + I(maRS), where I(PFz) and I(maRS) represent the asymmetry indices of the peak Fz and maximal rising slope, respectively. The differentiation between nonlame and lame dogs with this optimum combination had a smaller overlap than that obtained with the univariate approach (Figure 1). The AUC generated from this combination was 0.95 and was higher and significantly different from all of the other AUC scores, except the peak Fz score (Table 1). A cutoff value of 15.7% provided sensitivity of 92% and specificity of 86%; whereas a cutoff value of 19.5% provided sensitivity of 85% and specificity of 95% **(Figure 3)**.

Discussion

Lameness is often evaluated by use of kinetic gait analysis. The current lack of reference ranges has made it necessary to determine specific suitable reference control values. Studies[4-13] have thus far been conducted with sampling before or after treatment or with a single breed with available references. Similarly, the ROC procedure has been described with the GRF, but cutoff values were proposed only for Labrador Retrievers.[30] Assessment of the symmetry coefficient is a non–breed-specific method to evaluate lameness because it is based on right versus left comparisons. It reflects the comprehensive elements of the locomotor function. Asymmetry is generated by modifications of dog balance (ie, a load decrease in the injured hind limb and compensatory load increase in the contralateral hind limb).[22,23]

The Fy yielded lower test performances, compared with the Fz. Median AUC calculated with the Fy variables was < 0.5. Tests with an AUC of approximately 0.5 do not provide better-than-random predictions.[27] The Fy force has been advocated as a meaningful variable for lameness evaluation.[4,5,10] Results of the study reported here do not contradict this assumption but support the idea that asymmetry coefficients are not appropriate to analyze craniocaudal forces. Symmetry assessment was only informative with the Fz.

Peak Fz was the most accurate primary variable. This supports its use as a first-choice variable for kinetic studies.[6-9,12,13] Vertical impulse and maximal rising slope were also discriminating variables. Vertical impulse is used as commonly as is peak Fz, but the maximal rising slope is rarely used.[5,25] However, maximal rising slope complemented peak Fz better than vertical impulse did. Peak Fz and vertical impulse were highly correlated (0.90), whereas peak Fz and maximal rising slope were poorly correlated (0.35). Determination of the optimum combination did not include vertical impulse; instead, it used peak Fz and maximal rising slope. This is consistent with another study[30] in which an optimum association linked peak Fz with mean falling slope. Slope data may be of value because lameness typically causes a decrease in mean rising slope and an increase in mean falling slope.[5,10] Compared with peak Fz and vertical impulse, maximal rising slope could provide a new approach when studying vertical forces.

The multivariate approach was superior to a univariate approach. The optimum combination of peak Fz and maximal rising slope generated the greatest AUC, and in addition, comparison of the ROC curves for peak Fz and the optimum combination pinpointed the improvement in major relevant areas (Figure 3). Overlap between lame and nonlame dogs was decreased with the optimum combination, compared with overlap for peak Fz, vertical impulse, and maximal rising slope separately. Some lame dogs had symmetric data for peak Fz but large asymmetry for maximal rising slope. Furthermore, this combination makes sense clinically. Peak Fz represents the maximal amount of force the limb supports, and maximal rising slope represents the maximal loading rate (ie, how fast the limb could load). This combination corresponds to the ability of a dog to strike the ground during the stance phase.

Partial asymmetry during trotting was detected. Analysis of peak Fz revealed that a threshold (cutoff value) < 3.2% had sensitivity of > 95%. This means that a dog with an asymmetry value < 3.2% had a large probability of being nonlame. This corroborates results of other studies in dogs[15-17] and horses.[31] However, this threshold may be difficult to extrapolate because 2 simultaneous footfalls were recorded. This may artificially reduce the index because the forelimbs remain roughly symmetric during hind limb lameness. However, ipsilateral limbs are easy to record during gait analysis sessions, and a global asymmetry coefficient is thus easy to calculate.

Asymmetry assessment was effective in discriminating between nonlame and lame dogs. A cutoff value of 15.7% yielded sensitivity of 92% and a high probability that the dog was nonlame, whereas a cutoff value of 19.5% yielded specificity of 95% and a high probability that the dog was lame. A gray area persisted between these 2 thresholds. Hind limb lameness was evaluated regardless of its origin. The GRF is not a joint-specific measure, but an appropriately designed joint-specific study of lameness may decrease this gray area and improve the test properties. However, the goal of the study reported here was to establish a method to distinguish nonlame and lame dogs with subtle weight-bearing lameness, regardless of the origin of the lameness. Selection of a cutoff value must be made with regard for the estimated prevalence of lameness in the sample population. For example, for postoperative comparison of 2 techniques (a standard technique vs a new technique), sensitivity may be the key varaible because the assessment would be based on reliably detecting resolution of lameness.

Vertical force was a good variable for asymmetry assessment. A multivariate approach including peak and slope data was more valuable than a univariate approach. Partial asymmetry was found in the range of physiologic data. Although force redistribution is a complex process, asymmetry assessment in trotting dogs made it possible to establish the soundness of the locomotor system at a single point without other control data. This should be of value for multicentric or multiobserver studies or when preoperative data are unavailable.

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a. ADAL-3D-Running Treadmill, Tec Machine, France
b. PC-compatible with Ni-Daq 16-bits acquisition card, National Instruments, Austin, Tex.
c. R Development Core Team user manual. *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing, 2004.

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