Influencing factors on the foot health of captive Asian elephants (Elephas maximus) in European zoos

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Abstract: Pathological lesions of feet occur frequently in captive elephant populations. To improve foot health, it is important to identify risk factors associated with such pathologies. Several previous studies have analyzed potentially influencing factors but were limited, for example, by small sample sizes. This study analyzed the relationship between 87 independent variables and the foot health score of 204 Asian elephants (Elephas maximus) in European zoos using bivariate correlation, multivariable regression models, and principal component analysis (PCA). Correlation and regression tests revealed significant results for 30 different variables, mainly with small effect sizes. Only three variables were significant in more than one test: sex, time spent indoors, and time spent on hard ground, with lower scores (i.e. less or less severe pathological lesions) in females, and when less time is spent indoors or on hard ground. Due to small effect sizes and differing results of the statistical tests, it is difficult to determine which risk factors are most important. Instead, a holistic consideration appears more appropriate. A biplot of the PCA shows that factors representing more advanced husbandry conditions (e.g. large areas, high proportions of sand flooring) were associated with each other and with decreased foot scores, whereas indicators of more limited conditions (e.g. high proportions of hard ground, much time spent indoors) were also associated with each other but increased the foot score. In conclusion, instead of resulting from just one or two factors, reduced foot health might be an indicator of a generally poorer husbandry system.

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RESEARCH ARTICLE

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Influencing factors on the foot health of captive Asian elephants (*Elephas maximus*) in European zoos

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Abstract
Pathological lesions of feet occur frequently in captive elephant populations. To improve foot health, it is important to identify risk factors associated with such pathologies. Several previous studies have analyzed potentially influencing factors but were limited, for example, by small sample sizes. This study analyzed the relationship between 87 independent variables and the foot health score of 204 Asian elephants (*Elephas maximus*) in European zoos using bivariate correlation, multivariable regression models, and principal component analysis (PCA). Correlation and regression tests revealed significant results for 30 different variables, mainly with small effect sizes. Only three variables were significant in more than one test: sex, time spent indoors, and time spent on hard ground, with lower scores (i.e. less or less severe pathological lesions) in females, and when less time is spent indoors or on hard ground. Due to small effect sizes and differing results of the statistical tests, it is difficult to determine which risk factors are most important. Instead, a holistic consideration appears more appropriate. A biplot of the PCA shows that factors representing more advanced husbandry conditions (e.g. large areas, high proportions of sand flooring) were associated with each other and with decreased foot scores, whereas indicators of more limited conditions (e.g. high proportions of hard ground, much time spent indoors) were also associated with each other but increased the foot score. In conclusion, instead of resulting from just one or two factors, reduced foot health might be an indicator of a generally poorer husbandry system.

KEYWORDS
elephant, flooring, health, husbandry, management

1 | INTRODUCTION

As the largest terrestrial mammal with sophisticated cognitive abilities and a complex social structure, elephants are a very popular species kept in many of the larger zoos worldwide. By holding elephants in captivity, we take responsibility for their welfare and for providing conditions that prevent suffering due to health issues and pain. There is intensive research on infectious diseases and the investigation of reproductive aspects has already yielded major successes, for example in the establishment of artificial insemination techniques (Hildebrandt et al., 2006; Long, Latimer, & Hayward, 2016; Thongtip et al., 2009). Another very important topic of elephant medicine is foot health, as foot problems have a high incidence in different captive populations (80.4% in the UK, Harris, Sherwin, & Harris, 2008; 98.5% in Europe, Wendler et al., 2019;

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67.4% in North America, Miller, Hogan, & Meehan, 2016) and can represent a reason for euthanasia (Mikota, Sargent, & Ranglack, 1994). Common lesions are overgrown nails, pads or cuticles, nail or pad abscesses, fluid pockets in the cuticles and nail cracks (Lehnhardt, 2006; Roocroft & Oosterhuis, 2001; Rutkowski, Marion, & Hopper, 2001; Wendler et al., 2019).

To reduce the risk of such problems, an epidemiological approach is utilized to collect information from various institutions, build multivariable models to assess relationships, and detect potential influencing factors (Meehan, Mench, Carlstead, & Hogan, 2016). Several studies have previously investigated factors that could affect elephants' foot health (Table 1). Few associations were found, with some of them differing between studies. Most of the investigations were based on data collection performed by local zoo staff (Haspeslagh et al., 2013; Lewis, Shepherdson, Owens, & Keele, 2009; Miller et al., 2016) or on small samples of animals (Harris et al., 2008; Haspeslagh et al., 2013; Lucas & Stanyon, 2017; Miller et al., 2016; Yon, Williams, Harvey, & Asher, 2019). A typical problem when analyzing influencing factors is to distinguish between factors that might indicate a causal relationship, and proxy indicators or confounding factors. In particular, common sense would predict that a range of details considered typical for more advanced husbandry should covary. For example, a facility with large exhibits may also have a higher amount of natural flooring, a larger group size, and a lower mean group age. If in this case a significant correlation is found between group size and foot health, does it really mean that higher group size is beneficial for foot health or is it just representative for generally good husbandry conditions?

The aim of this study was to investigate a broad variety of potentially influencing factors on the foot health of Asian elephants (*Elephas maximus*). The investigation was based on a large and representative sample of elephants of the European Endangered Species Programme (EEP) population. Standardized and repeatable methods were ensured by personal site visits, to ensure accurate cross-institution comparisons.

2 | MATERIALS AND METHODS

2.1 | Ethics statement

The project was authorized by the management of each participating institution. Additionally, it was approved by the Elephant Taxon Advisory Group of the European Association of Zoos and Aquaria (EAZA) and the British and Irish Association of Zoos and Aquariums (BIAZA). The study was noninvasive.

2.2 | Data collection

Between August 2016 and July 2017, 69 zoos were visited by two veterinarians, and data was collected for 243 elephants (≥5 years old). To evaluate each elephant's foot health, pictures of every nail in cranial and solar perspective as well as of the pad (only in solar perspective) were taken and analyzed for pathological lesions (Wendler et al., 2019). To facilitate an associative epidemiological investigation, these lesions were given a score between 0 and 3, according to their severity (Ertl et al., 2019). To determine the foot health status that included all findings of one elephant, a new scoring system was developed, considering the number of lesioned locations as well as the severity of the lesions (Ertl et al., 2019). This total score was defined as "Particularised Severity Score" (ParSev Score). The care status of an elephant's feet was described using a "Care Score," and a "Pad Score" summarized the roughness of footpads (Ertl et al., 2019). Additionally, data concerning potentially influencing factors was collected by interviewing keepers, curators, or veterinarians regarding herd and individual parameters (Supporting Information Appendices 1 and 2). Underlying questions for these interviews were developed beforehand in consultation with zoo veterinarians and elephant caretakers of different zoos, while also taking literature on elephant management into account (Csuti, Sargent, & Bechert, 2001; Lehnhardt, 2006).

2.3 | Statistical analysis of influencing factors using bivariate correlation

Statistical analyses were conducted using R software Version 3.4.4. Based on the data from the studbook and interviews, 87 potentially influencing factors were defined as independent variables (Supporting Information Appendix 3). They included individual characteristics, foot care, management, enclosure, diet, and climate. Variables of ordinal or continuous character were related to the ParSev Score using Spearman's rank correlation. Variables of dichotomous characters were analyzed using the point-biserial correlation coefficient. The effect size was evaluated as small ($.1 \le |r| < .3$), medium ($.3 \le |r| < .5$) or large ($|r| \ge .5$) according to Cohen (1988, 1992).

2.4 | Statistical analysis of influencing factors using multivariable linear regression models

To further analyze the impact of independent variables on foot health, two multivariable linear mixed regression models were used with step-wise regression. The first model considered single nail values (range 0–3) as the dependent variable, whereas the second one used the ParSev Score in a γ-distributed model. The number of independent variables needed to be reduced to fit the models. Reasons for exclusion of a variable were small variability (e.g. particular chronic diseases and stereotypes occurring only in a very small number of elephants), few data points (e.g. diet components, where exact data on quantity and body mass could only be provided by a few institutions) and a presumed low importance (e.g. precipitation and temperature with far from significant results in the single correlation). To avoid calculation errors based on zero values, one was added to all scores. As some of the included variables were zoo specific (e.g. enclosure sizes, ground types) and therefore with equal values for the majority of elephants within the same institution, those variables were subsumed as random effect "zoo"

TABLE 1 Previous studies on influencing factors on the elephant's foot health and their results

Study	Method	Sample size	Influencing factor	Effect on foot health
Harris et al. (2008)	3 visits in 13 UK zoos	41 Asian and 36 African elephants	Age	Negative effect on foot health
			Species	No significant effect
			Total indoor space	No significant effect
			Total outdoor space	No significant effect
			Indoor space/individual	No significant effect
			Locomotion score	No significant effect
			Time spent stereotyping	No significant effect
			Mean FCM concentration (fecal cortisol metabolite—stress level)	No significant effect
			Body condition score	No significant effect
			Contact type	Positive effect of "no contact" on foot health (but could not be assessed equally)
Lewis et al. (2009)	Survey in 78 North American facilities	137 Asian and 151 African elephants	Herd age	Negative effect on foot health (1 year increase in herd age → 15% increase in likelihood of pathological lesions)
			Species	African herds showed slightly better foot health than Asian herd, but this is due to the herd age
			FTE/elephant (full time equivalents—keepers)	No significant effect
			Management system	No significant effect
			Exercise	Positive effect on foot health (10 min more exercise per day → 37% decrease in likelihood of pathological lesions)
			Indoor size	No significant effect
			Indoor concrete	No significant effect
			Tethering	No significant effect
Sarma et al. (2012)	Survey and examination in eastern India	312 Asian elephants	Age	Negative influence on foot health
			Sex	Females better foot health than males
			Limbs	Front limbs better than hind limbs
			Keeping conditions	Negative effect of muddy conditions on foot health
			Work assignment	Negative effect of logging on foot health
Haspeslagh et al. (2013)	Questionnaire in 32 European zoos	87 Asian elephants	Floor type	Negative effect of concrete and sand on foot health
				No significant effect of rocks, grass, tiles, asphalt, dirt, rubber, and straw
			Stereotypic behavior	Negative effect on foot health
			Age	No significant effect

(Continues)

TABLE 1 (Continued)

Study	Method	Sample size	Influencing factor	Effect on foot health
Miller et al. (2016)	North American zoos, examination through local zoo vet	32 African and 32 Asian elephants included in statistical analysis	Space experience, night	Negative effect on foot health
			Percent time in/out choice, day	Negative effect on foot health
			Time on hard substrate	Negative effect on foot health
			Sex	No significant effect
			Species	No significant effect
			Origin	No significant effect
			Environment contact	No significant effect
			Mean daily walking distance	No significant effect
			Body condition score	No significant effect
Lucas and Stanyon (2017)	Case report of a UK zoo	2 African elephants	Indoor floor type changed from concrete to sand, indoor area increased, feeding and management improved	Positive effect on foot health
Yon et al. (2019)	Data from BIAZA's Elephant Welfare Group of 5 UK zoos	20 Asian and 9 African elephants	Dependence on routine (feeding frequency, feeding at scheduled times, waiting for scheduled events, less playing with others)	Negative effect on foot health
			Length of longest lying bout	Positive effect on foot health

and their particular impact could not be analyzed in this model (Supporting Information Appendix 3).

2.5 | Statistical analysis of influencing factors using a multivariable linear regression model with mean values for each zoo

To investigate variables that were previously subsumed as random effect "zoo" concerning their influence on the ParSev Score, mean values for each institution were calculated and put into context with the mean ParSev Score for the institution. Again, a γ-distributed linear regression model was used, including the same variables as in the first regression model except for individual variables (e.g. sire, origin, dominance) and including diet components and time on hard ground instead.

2.6 | Statistical analysis using principal component analysis

A principal component analysis was used including 25 variables and the ParSev Score to further investigate relations between these factors. As some variables (e.g. areas) showed a highly skewed distribution, the logarithm was used to transform the data. If these variables included zero values, a value of 1 was added before log-transformation. Calculated component scores and loadings were visualized using a biplot.

2.7 | Interpretation of associations

The interpretive approach to significant associations varies depending on the expected relation to the variable of interest, which is the elephants' foot health in the present study. Formally, it cannot be decided, based on the data alone, whether an association indicates causality (as in: hard flooring causes foot problems, which explains a positive association between floor hardness and foot problems), a putative reaction (as in: animals with compromised foot health are kept on soft flooring to address the health issue, which explains a negative association between floor hardness and foot problems), or whether it is just a coincidental finding because one of the variables is associated to a third variable like a "proxy" (as in: institutions with harder floors keep older animals, and because older animals have more foot problems for other reasons, this results in a positive association between floor hardness and foot problems). Evidently, the absence of an association (in our example, between floor hardness and foot health) might then be caused by a mix of facilities where causation is active, and facilities where reactions have been instigated. This leads to the methodological dilemma: We know, before analyzing the result, that any outcome can be put into a narration that corroborates a preconception (in our example, the preconception that hard floors cause foot problems). We are aware of this fundamental problem of associative, epidemiological surveys, and caution readers against considering associations as more than circumstantial evidence. Using different multivariate statistical approaches does not prevent this fundamental issue, because the dilemma whether a significant influence factor is causative or reactive, or a nonsignificant factor is a mix of both, remains. Therefore, results such as those of the present study should inform readers about putative measures that can be taken to ameliorate a certain situation, the validity of which can only be assessed by experiments or case series.

3 | RESULTS

3.1 | Bivariate correlation

The correlation to the ParSev Score was tested for 19 dichotomous variables using the point-biserial correlation coefficient and for 64 variables using Spearman rank correlation. A significant correlation was found for 25 of these variables (Table 2). The highest correlation coefficient r was found for the amount of browse provided per elephant and day ($r_s = -.60$ [strong effect], $p < .001$), followed by the amount of time spent on hard ground ($r_s = .39$ [medium effect], $p = .001$), the amount of sand in the enclosure ($r_s = -.31$ [medium effect], $p < .001$), and the size of the indoor area ($r_s = -.30$ [medium effect], $p < .001$). For all other variables, the correlation coefficient was less than 0.3 (small effect).

3.2 | Multivariable linear regression model

The generalized linear mixed model, analyzing the relation of variables to single nail values, detected sex, two sires, and two countries as significant predictors. In particular, significantly lower (i.e., healthier) nail values were found for females in comparison to males ($p = .001$), for elephants that were fathered by Male A ($p = .001$) or Male B ($p = .033$), and elephants kept (European) countries 1 ($p = .009$) or 2 ($p = .010$).

The γ-distributed generalized linear mixed model, which considered the ParSev Score as the dependent variable, revealed sex ($p = .001$), chronic diseases ($p = .004$) and relatives ($p = .046$) as significant. Again, females were found to have a lower score than males. Elephants suffering from a chronic disease showed significantly higher foot scores, whereas animals that were kept together with an immediate relative had lower scores.

3.3 | Multivariable linear regression model with mean values

Using mean values for each institution in a linear regression model, significant correlations to mean ParSev Scores were found for the amount of time spent on hard ground ($p = .001$, $n = 28$), mean time spent indoors ($p = .002$, $n = 60$) and body mass ($p = .022$, $n = 32$) when analyzed separately. Higher ParSev Scores were associated with an increasing amount of time on hard ground and time spent indoors as well as with decreasing body mass. When these three variables were merged in one model, none of them showed any significant correlation ($n = 12$).

3.4 | Principal component analysis

The first principal component (PC1) explained 22.6% and the second component (PC2) an additional 10.2% of the variance. Hence, the biplot of PC1 and PC2 described nearly a third of the variance of this data set (Figure 1). Points in the plot signify individual elephants, whereas eigenvectors show relations between the variables. Eigenvectors pointing in similar directions are positively correlated in the first two principal components, whereas eigenvectors pointing in opposite directions are negatively correlated. Therefore, a higher ParSev Score (i.e. more or more severe pathological lesions) is for example associated with more time indoors, a higher amount of hard ground in the enclosure, less area per animal, less time with free access to in- and outdoor enclosure and less cooperativity during foot care. The longer the eigenvector, the higher is the contribution of the corresponding variable. For example, area per animal has a higher contribution than cooperativity during foot care in the first two principal components. The eigenvector of the ParSev Score lies in the third quadrant of the coordinate system, together with time spent indoors, amount of hard ground in the enclosure and number of years of experience of the keepers, to name the three strongest eigenvectors. Pointing to the opposite, first quadrant, predominant eigenvectors are mean enclosure area, the time the elephants can choose whether to stay in- or outdoors, area per animal as well as the amount of sand in the enclosure. The second quadrant shows variables which were, with regard to the ParSev Score, positively related in the first, but negatively related in the second principal component. The most important eigenvectors here are the mean age of the group, age and amount of time spent stereotyping per day. Conversely, in the fourth quadrant, we can find the size of the indoor and outdoor areas as well as the mean group size.

4 | DISCUSSION

Based on the data of a comprehensive proportion of the EEP population of Asian elephants (82.9% of all elephants aged 5 years or older; Wendler et al., 2019) and using a foot scoring system suitable for epidemiological approaches (Ertl et al., 2019), necessary requirements for the analysis of influencing factors on the foot health were met. To identify risk factors for pathological lesions of feet, various independent variables covering distinct topics were investigated. But dealing with a high number of independent variables is difficult and often requires the use of different statistical analyses. Simple statistics, such as the single variable correlation used in this paper, do not consider multicollinearity, which means that relationships among the independent variables are not taken into account. Therefore, the validity of these tests is limited. Multivariable linear regression models help to identify individual risk factors but can also be influenced by multicollinearity. In contrast to that, the principal component analysis deals with the problem of multicollinearity but does not identify individual predictor variables with a significant influence on the dependent variable (Dohoo, Ducrot, Fourichon, Donald, & Hurnik, 1997). To compensate for the shortcomings of each statistical test, all three methods were applied in the present study. However, for most

TABLE 2 Variables with significant bivariate correlation using Spearman's rho r_s or point-biserial correlation coefficient r_{pbi} for dichotomous variables to the ParSev Score ($p < .05$)

Variable	n	r_s / r_{pbi}	p Value	Effect size
I. Individual characteristics				
Chronic skin disease (present, not present)	204	.16[a]	.021	Small
Sex [(male, female)	204	−.15[a]	.031	Small
Stereotypic nodding (hr/day)	204	.15	.035	Small
II. Foot care				
Care Score (0–62)	191	.20	.004	Small
Cooperativity (1–5)	204	−.19	.006	Small
Pad Score (4–16)	204	.16	.019	Small
Washing (daily, every 2nd or 3rd day, weekly, less frequent, never)	204	−.16	.025	Small
Wet feet (daily, every 2nd or 3rd day, weekly, less frequent, never)	204	−.15	.030	Small
III. Management				
Current time outdoors (hr/day)	204	−.14	.041	Small
Exercise (hr/week)	204	.16	.024	Small
Free choice availability (yes/no)	204	−.16[a]	.022	Small
Group size (/)	204	−.16	.020	Small
Time free choice (hr/day)	204	−.22	.001	Small
Time indoors (hr/day)	204	.25	<.001	Small
IV. Enclosure				
Area per animal (m^2)	192	−.15	.038	Small
Ground sand (%)	188	−.31	<.001	Medium
Ground grass (%)	188	.15	.041	Small
Indoor area (m^2)	192	−.30	<.001	Medium
Mean area (m^2)	192	−.26	<.001	Small
Time hard ground (%)	71	.39	.001	Medium
V. Diet				
Biotin (mg/animal)	192	.19	.008	Small
Browse ($g/kg^{0.85}$)	37	−.60	<.001	Large
Grass ($g/kg^{0.85}$)	114	−.22	.016	Small
Silage ($g/kg^{0.85}$)	196	−.24	.001	Small
Vegetables ($g/kg^{0.85}$)	88	−.24	.027	Small

[a]For dichotomous variables instead of Spearman's rho r_s the point-biserial correlation coefficient r_{pbi} was calculated; effect size evaluated according to Cohen: small: $.1 \le |r| < .3$, medium: $.3 \le |r| < .5$, large: $|r| \ge .5$.

variables, a significant correlation was only found in one of the statistical tests and effect sizes were often small. Therefore, it is difficult to draw an explicit conclusion concerning the risk factors for pathological lesions of feet from these results. Nevertheless, we discuss observed significant correlations as well as the general context.

4.1 | Individual characteristics

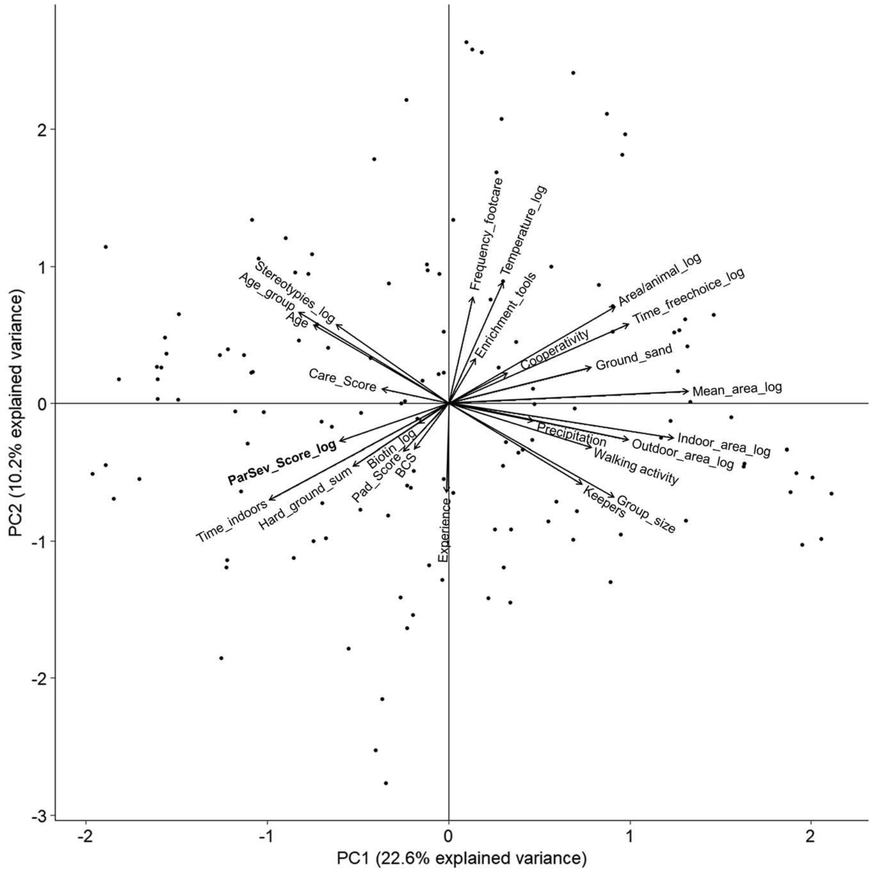
Sex was the only variable with a significant correlation to foot health in three different statistical tests. The bivariate correlation revealed a small but significant effect, and there was also significance in the regression models with single nail values and the ParSev Score. According to these statistics, females had less or less severe foot problems than males. No significant effect of sex was found by Miller et al. (2016), but there were only 7 males included in the analysis, whereas 48 male elephants were analyzed in our study. Within captive elephants in India, Sarma, Thomas, Gogoi, Sarma, and Sarma (2012) also found a higher incidence of foot problems in males, which were explained by chaining, and reduced hygiene and foot care, during the months of musth. In the included European zoos, no male elephant was chained during musth, but several keepers reported that during this period of higher testosterone levels, foot care is not as feasible as usually. As most males were kept either separately from females or in "bachelor groups," different husbandry conditions could also be the reason for the increased ParSev Scores. But using the Wilcoxon rank-sum test, we did not find a significant difference for the key elements time spent indoors, mean area and amount of sand as a substrate between the sexes. Hence, males might require different husbandry conditions than females to ensure healthy feet. However, the difference in the mean ParSev Scores (females: 18.3, males: 21.4; total score range: 0–69) was small, meaning that for example, a male had three minor nail cracks more than a female.

West (2001) reported increasing age as a risk factor for foot problems, which was confirmed by the study from Harris et al. (2008). In contrast, no statistical test in our study revealed a significant correlation between age and foot health, which corresponds to the results from Haspeslagh et al. (2013). Although increasing age is often mentioned by keepers and veterinarians as a risk factor for foot problems, the results of our study cannot confirm this, and age seems, if at all, only to be a proxy indicator for other influencing conditions.

A significant relationship was found when comparing mean body masses of animals in the same zoo with their mean ParSev Scores using a multivariable linear regression model. Higher mean body masses were associated with less or less severe pathological lesions. Due to the nonparametric nature of the correlation, no statistically supported equation can be given, but the overall pattern indicated a decrease of the ParSev Score by 2.6 points for every 500 kg difference, which is a rather small effect. The significant correlation should be interpreted with caution, as all analyses on individual basis did not show any relationship, and for the analysis of mean values, only 32 data points could be used. Moreover, this result contrasts with the common assumption that higher body masses lead to more foot problems due to higher peak pressures (Hughes & Southard, 2001; Roocroft & Oosterhuis, 2001; Sadler, 2001; West, 2001). No association was found between the body condition score (data from Schiffmann, Clauss, et al., 2018) and ParSev Score, which is in accordance with the results of Harris et al. (2008).

The regression model with single nail values revealed that descendants of Male A and Male B showed significantly healthier feet in comparison to other elephants (Figure 2), making a genetic component in the prevalence of foot problems conceivable. This has already been suggested by Seidon (2001) and Lehnhardt (2006), but

FIGURE 1 Biplot of the principal component analysis of data concerning foot health and related husbandry factors of captive Asian elephants (*Elephas maximus*) showing principal component 1 and principal component 2



has not been further analyzed so far and might present an objective for future research. For cattle, a low heritability of hoof health has already been proven (Malchiodi et al., 2017).

Within the regression model using the ParSev Score, elephants suffering from a chronic disease showed more or more severe foot problems. Again, there was only a small difference of four units in the mean ParSev Scores. Chronic diseases may decrease activity, which is suggested to correlate with more foot problems (Lewis et al., 2009; Roocroft & Oosterhuis, 2001). Another explanation could be a compromised immune system due to chronic suffering leading to a higher susceptibility towards foot lesions. There was also a significant result in the single correlation of one particular chronic disease, namely skin disease. This result should be considered very carefully, because there were only 11 elephants suffering from a chronic skin disease. But as the evaluated structures of the feet are ontogenetically modified forms of the common integument (Bragulla, Budras, Mülling, Reese, & König, 2004), a co-occurrence with chronic skin diseases, or relevance of general susceptibility to skin diseases, is conceivable.

Stereotypic behavior has previously been associated with a higher risk of foot problems (Haspeslagh et al., 2013; Roocroft & Oosterhuis, 2001). Nevertheless, there was no significant correlation between the estimated time the elephants displayed stereotypic behavior and foot health. But when analyzing particular stereotypic movement patterns (Haspeslagh et al., 2013) using bivariate correlation, a significant, but small effect was found between the amount of time spent in stereotypic nodding and the ParSev Score. As only 8 of 243 elephants showed stereotypic nodding behavior, this result should also be considered with caution. To elucidate the impact of stereotypic behavior on an elephant's foot health, it might be essential to collect data regarding the specific movement pattern and duration of stereotypic behavior.

4.2 | Foot care

Foot care is a common procedure to prevent and treat foot problems in elephants under human care (Fowler, 2001a; Roocroft & Oosterhuis, 2001; Schwammer, 2001; West, 2001). From the variables concerning foot care, only small effects in the bivariate correlation could be found for cooperativity, frequency at which the elephants have wet feet, frequency of washing and the Care Score and Pad Score. Elephants that were evaluated as being more cooperative during foot care showed less or less severe foot problems. This underlines the importance of good training that allows the performance of an effective pedicure (Roocroft & Oosterhuis, 2001).

Daily washing and scrubbing of the elephants' feet to remove dirt and monitor lesions are recommended by Roocroft and Oosterhuis (2001) and Schwammer (2001). The results of our study indicate that a higher frequency of washing or of wet feet through washing or pool usage is associated with a higher ParSev Score. Perhaps, washing of feet lost importance because of the improvement of husbandry, and nowadays, frequent wet feet lead more to a weakening of the foot

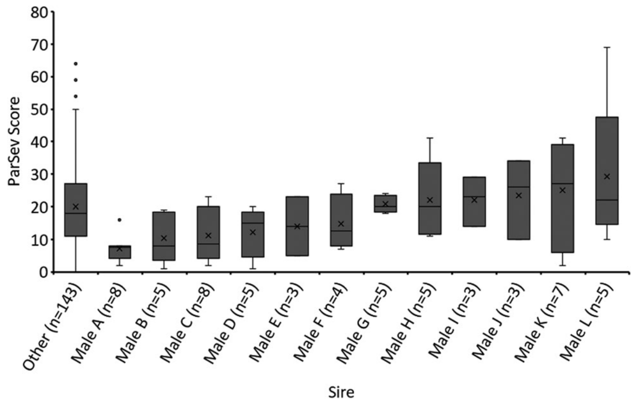


FIGURE 2 Relation between ParSev Score and sire in captive Asian elephants (*Elephas maximus*), only for sires with at least three descendants (*n*) in the study, all others referred to as "Other."

structures. Also, Sarma et al. (2012) noticed that captive elephants in India had more foot problems when they lived under muddy conditions. Another explanation could be that frequent washing is a consequence and not a reason for poor foot health; in other words, that elephants with foot problems may receive more washing to improve hygiene.

Care Score and Pad Scores were developed to evaluate care condition and roughness of footpads (Ertl et al., 2019). Smaller ParSev Scores were found when elephants showed less care issues and smoother pads, which result from adequate husbandry providing natural wear supported by foot care that balances probable deficiencies.

4.3 | Management

Time indoors was one of only three variables that reached significance in more than one statistical test, indicating that elephants kept less time indoors showed lower ParSev Scores (Figure 3a). Compared to North American zoos (Meehan, Hogan, Bonaparte-Saller, & Mench, 2016), elephants kept in European zoos spent nearly twice as much time indoors (28.9% vs. 53.4%), which could be a reason why a significance was found in this study but not for the North American population (Miller et al., 2016).

In turn, the availability and a higher amount of time to choose whether to stay in- or outdoors, was associated with smaller ParSev Scores, using bivariate correlation. Although hypothesizing the same relationship, Miller et al. (2016) found an increased risk of foot abnormalities with increasing free-choice time for elephants in North American zoos. The differing results might be due to the fact that within the North American population, the alternative for free choice time is much more time outdoors (time free choice: 16.0%, time outdoors: 55.1%, time indoors: 28.9%), whereas within the European population the elephants spend alternatively much more time indoors (time free choice: 21.3%, time outdoors: 25.2%, time indoors: 53.4%). Yon et al. (2019) found a positive relationship between dependence on routine (including feeding frequency feeding at the scheduled time, waiting for scheduled events and less playing with others) and the severity of foot problems. Having the opportunity to choose between indoor and outdoor stay, and not being put outside and back inside at specific times, decreases the dependence on routine. Therefore, our result of a positive influence of unrestricted access to both enclosures corresponds to the finding of Yon et al. (2019).

The time the elephants spent outdoors on the day of examination was recorded to consider seasonal differences, as it was not possible to visit all facilities in the same season. In the bivariate correlation, a significant, but small effect on the ParSev Score was found, indicating that elephants that spent more time outdoors had a lower score. Reasons for a longer time outdoors could be that the zoo was either visited in summer, when elephants usually have the longest time outdoors or that the zoo generally provided longer outdoor stays.

The regression model with ParSev Scores revealed that elephants that were kept together with immediate relatives (parents, offspring or siblings) showed less or less severe foot problems. In the wild, female elephants and their offspring build matriarchic herds consisting of closely related individuals, whereas males leave the group at the age of puberty (Vidya & Sukumar, 2005). So for females, having an immediate relative in the group, displays the natural social environment and should, therefore, help to maintain adequate exercise through social interaction, which is suggested as being beneficial for foot health (Roocroft & Oosterhuis, 2001; West, 2001).

A similar effect may be underlying present for group size (Lehnhardt, 2006). The mean size of wild Asian elephant herds in southern India lies between 5.8 and 8.8, depending on the season (Sukumar, 2003). In the European zoo population, a herd consisted of 3.4 elephants on average. Through bivariate correlation, a significant correlation was found, indicating that elephants in larger groups had lower ParSev Scores.

To maintain a preferable body and foot condition, adequate exercise is advised by several authors (Fowler, 2001b; Schwammer, 2001; West, 2001). As the environment of captive elephants is often not sufficiently exercise-inducing, Roocroft and Oosterhuis (2001) recommend at least 1 to 2 hr of keeper-supervised walking per day. In the present study, 15.6% of the examined elephants were exercised in this way. In free contact, the elephants were walked next to the keeper either through or outside of their enclosure. In protected contact, the elephants were sent to different points in their enclosure. Using bivariate correlation, a small effect was found between hours of exercise per week and ParSev Score, indicating that elephants that were exercised more had higher ParSev Scores. This correlation opposes our expectations and contradicts the results from Lewis et al. (2009). Although the effect was only small, it should be considered to exercise elephants, preferably stimulated by an adequate social structure and a varied feeding enrichment instead of induced by keepers, as this would imitate natural movement patterns better. Keeper-induced exercise may be implemented by institutions with poorer conditions (e.g. small enclosures, low social interaction within the herd) to compensate for these deficiencies, and thus could be a proxy indicator for these other conditions.

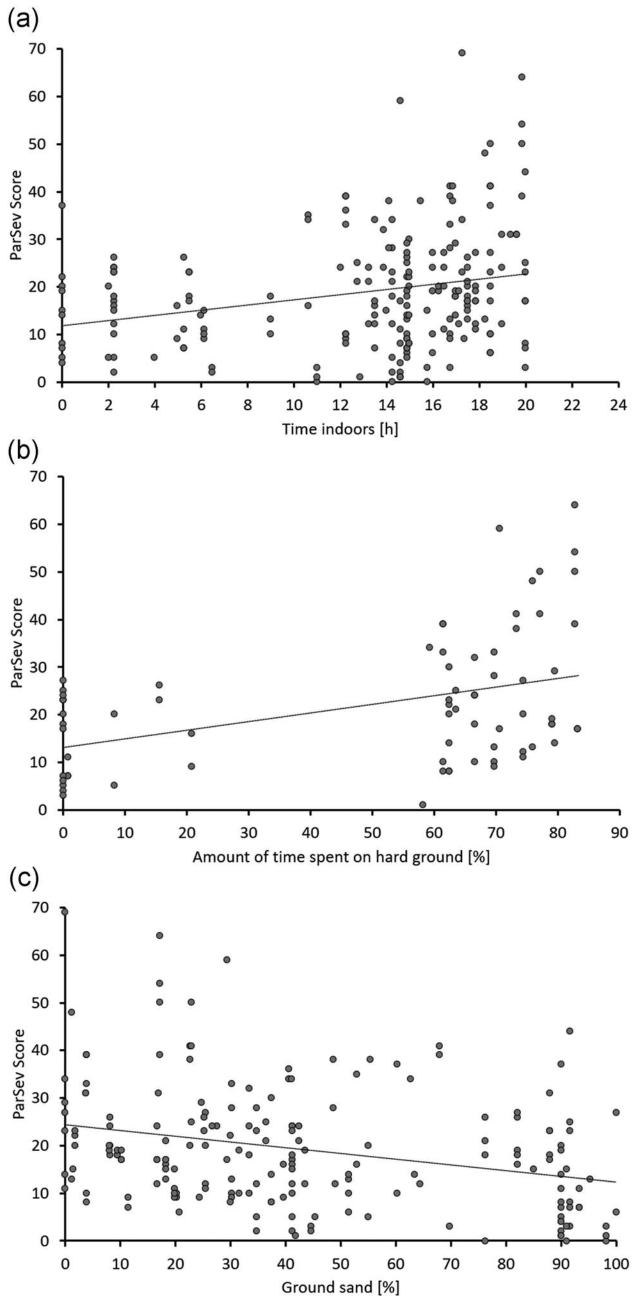


FIGURE 3 Relation between ParSev Score of captive Asian elephants (*Elephas maximus*) and (a) the time spent indoors, (b) the amount of time spent on hard ground, and (c) the amount of sand flooring in the enclosure

4.4 | Enclosure

Time spent on exclusively hard ground is the third and last variable with a significant result in more than one statistical test, whereby a higher amount of time spent on the hard ground led to higher ParSev Scores (Figure 3b). The bivariate correlation revealed a medium effect and there was also a significant correlation in the linear regression model with mean values for the institutions. Analogous to Miller et al. (2016), only enclosures with 100% hard ground (concrete, asphalt, rocks or tiles) were considered for the calculation of the amount of time the elephant spent in this area. This allows a comprehensible statistical analysis, as the elephant actually stands on hard ground without a soft-floored alternative. The problem in this method is that there are few data points, as most elephants were kept in enclosures with mixed floor types (63.4%), and that these data points are bimodally distributed (either very low or very high values, but no data points between 25% and 55% of time spent on hard ground). Additionally, the time spent on hard ground is related to the time spent indoors, as 100% hard ground is usually only used for indoor and not for outdoor enclosures. Hard ground is one of the main factors presumed to lead to foot problems (Gage, 2001; West, 2001) and has already been identified as a risk factor by Haspeslagh et al. (2013) and Miller et al. (2016).

Haspeslagh et al. (2013) also identified sand as risk factor, which is usually evaluated as beneficial for the foot health as this substrate yields, allows digging and is preferably used for lying down, which relieves the feet (Holdgate et al., 2016; Roocroft & Oosterhuis, 2001; Schiffmann, Hoby, et al., 2018; Schiffmann, Knibbs, Clauss, Merrington, & Beasley, 2018; Schwammer, 2001; Williams, Bremner-Harrison, Harvey, Evison, & Yon, 2015; Yon et al., 2019). In the present study, sand was indeed identified as a beneficial factor for foot health, as a higher amount of sand flooring correlated significantly with lower ParSev Scores (Figure 3c). In contrast to the amount of time on hard ground, data concerning sand flooring is continuously distributed, and therefore well apt for quantitative analysis. This emphasizes the importance of supplying considerable amounts of sand flooring in modern elephant enclosures.

For the amount of grass in the enclosure, a small effect in the bivariate correlation was found, indicating higher ParSev Scores when there was a higher amount of grass in the enclosure. This result should be evaluated with caution as only a quarter of the elephants had grass in their enclosure. Grass being a natural ground, we would have expected a positive effect on foot health. Haspeslagh et al. (2013) found no significant effect of grass on foot health. One reason for the negative effect could be waterlogging if the natural grass flooring drains worse than for example sand flooring. This would correspond to the higher ParSev Score in more frequently washed or wet feet but nevertheless presents a rather vague explanation. It is likely that the amount of grass is related to other factors negatively influencing foot health.

Whereas most previous studies did not reveal a significant effect of the enclosure size on foot health (Harris et al., 2008; Lewis et al., 2009), a larger area was significantly correlated with lower ParSev Scores in the present analysis. Showing a medium effect in the bivariate correlation, indoor area seems to be more influential than outdoor area, which was not significant. There was a significant but small effect of the mean area and the area per animal, which can be explained by the contribution of the indoor area in these variables. The mean indoor size was 385 m^2 for a mean group size of 2.9 animals, which surpasses the EAZA and BIAZA management guidelines requiring a minimum of 200 m^2 for four elephants (EAZA, 2005; Walter, 2010). A large indoor size, especially when structured and enriched, allows and encourages activity, which is considered beneficial for foot health (Roocroft & Oosterhuis, 2001; West, 2001). The importance of the indoor enclosure size becomes particularly apparent when considering time budgets of captive elephants. An elephant spends approximately 3–4 hr per 24 hr sleeping in lying position (Holdgate et al., 2016; Walsh, 2017) but is kept inside for 12.8 hr on average. Hence, there is considerable time left for activity, requiring a certain amount of space.

4.5 | Diet

The only variable showing a strong effect in the bivariate correlation was the amount of browse provided per day per unit metabolic body weight. A higher amount of browse is related with lower ParSev Scores, indicating a better foot health condition. As most zoos either fed browse irregularly depending on availability, or could not quantify the amount provided per elephant, there are very few data points and the result must be interpreted with caution. Nevertheless, the influence of browse is worth considering as long branches are crushed using the trunk and the front feet for fixation. This process might help wearing cuticles, nails and pads in a natural way while also stimulating blood circulation in the foot, and might therefore prevent the development of pathological lesions. To test this assumption, we correlated the amount of browse provided per day per unit metabolic body weight separately with the ParSev Scores of the front feet and the hind feet, hypothesizing that browse only influences the front feet which are involved in the crushing process. Both correlations were significant, so we could not prove the assumption (front feet: $r_s = -.54$, $p = .001$, hind feet: $r_s = -.50$, $p = .002$). Another possible explanation for the significant correlation would be that precise data on the amount of branches and the weight of the elephants was only provided by zoos with a generally advanced husbandry level and consequently lower ParSev Scores. For a general discussion of indicators of advanced husbandry standards, see below. To further examine the relation between browse and foot health, a larger data set would be necessary.

There were also small effects in the bivariate correlations of the amounts of grass, silage and vegetables provided per day per unit metabolic body weight and the ParSev Score, indicating lower foot scores when higher quantities were fed. Again, precise data was not available for all zoos, which could be influential on the resulting correlation. An elephant's diet should be based on high-fiber roughage to avoid obesity, which might negatively influence foot health (Hatt & Clauss, 2006; Sadler, 2001). In most collections, this is supplemented by additional components. In this context, grass, silage and vegetables might actually have a positive effect on foot health, especially when replacing easily digestible energy sources like fruits, bread, cereals, or concentrated pellets.

Biotin has been identified as beneficial for the hoof horn quality in horses (Geyer & Schulze, 1993) and is therefore also used in elephants assuming similar effects. Benz (2005) showed that supplemented elephants reached higher biotin blood concentrations than unsupplemented animals, and hence deduced good intestinal absorption. But so far, the actual influence of supplemented biotin on the elephant's foot health has not been proven. In the present study, a significant but small effect was found between the amount of biotin supplied per elephant per day and the ParSev Score, indicating higher foot scores with increasing biotin doses. We suggest that this is not due to a negative effect of biotin on the foot health but because it is fed especially to elephants with poor foot condition. A long-term study analyzing the changes in the foot health with varying biotin doses while other parameters (such as husbandry, foot care, and diet) remain unchanged would be necessary to further investigate this topic.

4.6 | Climate

No significant correlation was found between the ParSev Score and climate-related variables like the total annual precipitation and the annual average temperature. The regression model with single nail values identified two countries with significantly lower ParSev Scores. As there was only a small number of zoos included in both countries, the significant result was rather due to general conditions in these institutions and not because of topographical or climatic aspects.

4.7 | Holistic consideration

The easiest-to-interpret and desired result of these analyses would have been to identify one or two risk factors that show a significant result in every statistical test and therefore provide a tangible starting point for future improvement of foot health. But in fact, we found 30 different variables with significant results, most of which were only significant in one of the statistical tests and showing rather small effect sizes. Therefore, it might be reasonable to consider the overall concept instead of trying to evaluate which of these factors might be the most important one. Showing the interrelations of several selected variables, the principal component analysis appears suitable to provide a basis for this kind of consideration. The biplot (Figure 1) shows that eigenvectors indicating a rather advanced husbandry level point roughly in the same direction and are therefore related to each other. These would be, amongst others, enclosure sizes, time with unrestricted access to indoor and outdoor enclosures, sand flooring and group size. Opposite to these representatives of preferable husbandry conditions, there are factors associated with potentially problem-causing conditions like hard flooring, time spent indoors, stereotypies and age. Amongst these, there is also the eigenvector representing the ParSev Score and therefore pathological lesions of feet. So, generally poorer husbandry conditions seem to lead to more or more severe pathological lesions and to positively influence foot health, it might not be sufficient to change only one factor, but to revise the overall concept of elephant husbandry and care. In the short-term, it would be beneficial to increase the availability of browse as part of the diet and to decrease the time the elephants spend indoors preferably by increasing the time with unrestricted access to indoor and outdoor enclosures. In the long-term, enclosures should become larger, and hard substrates should be replaced by sand flooring. Furthermore, family groups should be established as positive effects were found for the presence of relatives in the group, higher group sizes, and lower mean group ages. Finally, on a very theoretical level, if genetic investigations proved the suggested heritability of foot health, foot conditions of future generations could improve by selecting breeders that sire advantageous phenotypes.

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