Identification of the sex, weight, and individuals through 3D modelling of cheetah (Acinonyx jubatus) tracks taking into account their degradation over time, and photogrammetric analysis of cheetah (Acinonyx jubatus) gaits by determining a new trail measuring technique

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ABSTRACT

The study of endangered species is crucial to their survival, and this can be done through monitoring that helps targeting conservation needs. Indirect monitoring methods make it possible to study animals that are difficult to observe. Traces of presence, such as footprints, contain a wide range of information about their author that can be used to characterise an individual. On the one hand, the objective of this study is to identify individuals, their sexes and weights based on 3D models of cheetah tracks including the study of these factors over time. On the other hand, the objective is to determine a new measurement technique for cheetah trails. Eight semi-captive Namibian cheetahs were studied. Geometric morphometrics highlighted shape differences through the use of 25 fixed landmarks and 130 surface sliders. The tracks were discriminated by performing a Linear Discriminant Analysis (LDA) with jack-knife prediction using size and conformation information from a Principal Component Analysis (PCA). Regarding footprint position, the best prediction effectively identifies 95.19% of the footprints. Individuals were correctly identified in 82.9% of the prints, sex in 87.9% of the prints and weight in 87.6% of the prints. The analysis of male prints increased the accuracy of weight identification to 100% for the best case studied. The comparison of direct measurements and digital measurements (with a drone and with a camera) of cheetah trails showed that each technique was equivalent and could substitute the other. Differences in male and female gait characteristics from overstep trails were statistically significant.

Keywords: Acinonyx jubatus, cheetah, track, trail, footprint, wildlife monitoring, indirect monitoring, geometric morphometrics, 3D model, photogrammetry, drone.

L'étude d'espèces en voie d'extinction est cruciale pour leur survie et cela passe par le monitoring qui permet de cibler les besoins en termes de conservation. Les méthodes de monitoring indirectes permettent d'étudier des animaux difficilement observables. Les traces de présence, comme les empreintes contiennent une large gamme d'informations à propos de leur auteur qui peuvent être exploitées pour caractériser des individus. D'une part, l'objectif de cette étude est d'identifier les individus, leurs sexes et leurs poids basés sur des modèles 3D de traces de guépards en incluant l'étude de ces facteurs dans le temps. D'autre part, l'objectif est de déterminer une nouvelle technique de mesure pour les démarches de guépards. Huit guépards Namibiens semi-captifs ont été étudiés. La morphométrie géométrique a mis en évidence les différences de conformation des traces grâce à l'utilisation de 25 points de repère fixes et de 130 de pseudo points de repères. Les traces ont été discriminées par la réalisation d'une Analyse Linéaire Discriminante (ALD) avec prédiction jack-knife en utilisant des informations de taille et de conformation issues d'une Analyse en Composantes Principales (ACP). Concernant la position de l'empreinte, la meilleure prédiction identifie efficacement 95.19% des empreintes. L'identification des individus est correcte pour 82.9% des empreintes, celle des sexes pour 87.9% des empreintes et celle du poids pour 87.6% des empreintes. L'analyse des empreintes des mâles a permis d'augmenter la précision de l'identification du poids jusqu'à un taux de 100% pour le meilleur cas étudié. La comparaison des mesures directes et mesures digitales (avec un drone et avec une caméra) des démarches de guépards a démontré que chaque technique était équivalente et pouvait suppléer une autre. Les différences entre démarches (à vitesse similaire) de mâles et de femeles, se sont avérées significatives statistiquement.

Mots-clés: Acinonyx jubatus, guépard, empreinte, démarche, monitoring de la faune sauvage, monitoring indirect, morphométrie géométrique, modèle 3D, photogrammétrie, drone.

TABLE OF CONTENTS

INTRODUCTION

The cheetah *Acinonyx jubatus* is a conservation priority. It is classified as vulnerable by the IUCN Red List (Durant *et al.*, 2015), although it is encouraged to be reassessed to endangered (Durant *et al.*, 2017; Weise *et al.*, 2017). The current population is estimated at 7,100 mature individuals (Durant *et al.*, 2017). This number is in constant decline (Durant *et al.*, 2017). This is due to the threats that weigh upon this species: habitat loss and fragmentation (Jeo *et al.*, 2018; Marker, Grisham and Brewer, 2018), illegal wildlife trade (Tricorache *et al.*, 2018), human-wildlife conflict (Marker and Boast, 2015; Klaassen and Broekhuis, 2018), and decrease of prey populations (Marker *et al.*, 2003; MARKER and DICKMAN, 2004; Durant *et al.*, 2017). These threats are a result of the 6th mass extinction caused by the expansion of humans (Briggs, 2017; Cowie, Bouchet and Fontaine, 2022). In addition to human-related threats, cheetahs are subject to high competition with other large carnivores and to a high cub mortality rate (Sinclair and Arcese, 1995; Swanson *et al.*, 2014). Interspecific competition made them move closer to farmland, thus increasing livestock depredation and disease transmission (L. L. Marker *et al.*, 2008; Van der Weyde *et al.*, 2016).

Cheetahs faced bottlenecks in the past resulting in poor genetic diversity (Laurie L. Marker *et al.*, 2008; Schmidt-Küntzel *et al.*, 2018). This explains the species vulnerability to rapid environmental changes (Durant *et al.*, 2017; Schmidt-Küntzel *et al.*, 2018). There are four subspecies: the Asiatic cheetah (*A. j. venaticus*), the Northwestern African or Saharan cheetah (*A. j. hecki*), the Eastern African or Sudan cheetah (*A. j. soemmeringii*) and the one concerned in this study, which is the most represented one, the Southern African cheetah (*A. j. jubatus*) (Marker, Grisham and Brewer, 2018).

The distribution of the cheetah has shrunk to 9% of its historical range (Durant *et al.*, 2017). The cheetah is mostly found outside of protected areas where it can be persecuted by farmers (Marker *et al.*, 2007; Durant *et al.*, 2017; Weise *et al.*, 2017). Namibia has the largest population of free-roaming cheetahs (Marker *et al.*, 2007; Fabiano *et al.*, 2020).

Monitoring a species allows to have an overview of its population. It is needed to make decisions on the conservation efforts related to this species (Prosekov *et al.*, 2020). Monitoring can be realised through direct counts of the animals, following a transect for example, or through indirect observations of the animal's presence, such as faeces or footprints (Liebenberg, 1990; Prosekov *et al.*, 2020). Indirect signs are useful in the case of shy animals that are difficult to observe (Petso, Jamisola and Mpoeleng, 2021). Cheetahs are elusive animals with a large home range and low densities which make them hard to see (Hofman *et al.*, 2019). However, their footprints are often found in the wild. Tracks contain unique information about species, age, sex and even individual. Ancient San trackers learned how to recognize these features from tracks (Liebenberg, 1990) and this knowledge is being used to develop a technique called Footprint Identification Technique (FIT) (Alibhai, Jewell and Law, 2008; Gu *et al.*, 2014; Jewell *et al.*, 2016, 2020; Li *et al.*, 2018). It is a non-invasive, cost-effective, and fast technique that does not require any tracking skills (Pimm *et al.*, 2015; Petso, Jamisola and Mpoeleng, 2021). Track observation does not interfere with the animal behaviour, and it respects the individual welfare (Gu *et al.*, 2014).

Pictures of tracks are being used to create identification algorithms. A wide range of algorithms have successfully been developed for several mammals (Alibhai, Jewell and Evans, 2017).

Recent studies have introduced the use of three dimensions (3D) in the footprint identification technique, which allows to extract more information from the footprint (particularly the depth), and reduce operator bias (Marchal, Lejeune and Bruyn, 2016; Marchal, 2017; Baralle *et al.*, 2021).

New technologies are useful for conservation. Improvements in camera capabilities allow higher quality data acquisition, while drones provide monitoring and surveillance possibilities and AI (Artificial Intelligence) improves data processing and automation (Petso, Jamisola and Mpoeleng, 2021). In this study, we used a drone to sample cheetah trails. A trail is a continuous sequence of tracks left on the ground by an individual while walking.

The aim of this study is to develop identification algorithms using 3D cheetah tracks and trails. We used geometric morphometrics (through R package *geomorph version* 4.0.4) to extract information about position, sex, weight and individual from 3D cheetah tracks, by taking into consideration the track degradation over time. We used aerial and terrestrial photogrammetry to measure the cheetah trails and develop a new measuring technique. The possibility to include gait characteristics in the identification algorithms will be assessed.

MATERIALS AND METHODS

Study conditions

The study was conducted in N/a'an ku sê Wildlife Sanctuary (hereafter Naankuse), located in the Khomas Region in Namibia. Wild animals are rescued by the sanctuary if they are injured, orphans or involved in the human-wildlife conflict. They are then released into the wild whenever possible.

Eight semi-captive cheetahs were used for this study, four females and four males (Figure 1). The cheetahs came from three different enclosures. The cheetahs from a same enclosure were either siblings or raised together.

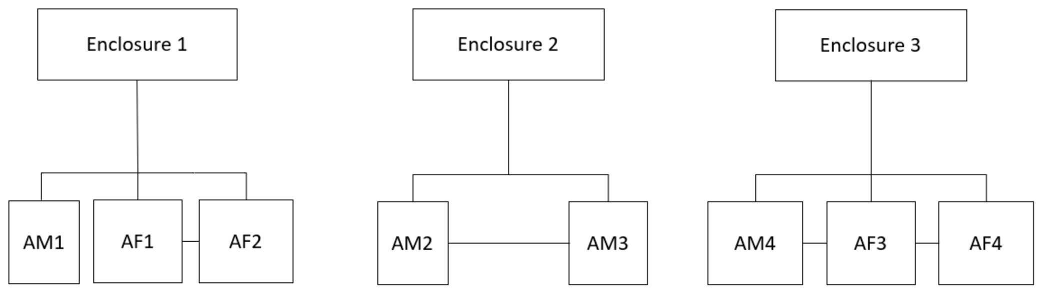


Figure 1: Organisation chart of the three enclosures visited during this study. The connected boxes mean that the cheetahs are related. AM = Adult Male, AF = Adult Female.

An area of 8 metres long and 3 metres large without trees was selected to become the sampling strip (Figure 2). The sampling strips were prepared to present uniform conditions.

The area was cleaned using shovels and rakes to remove vegetation. In the first enclosure no additional sand was needed because the present sand was thin enough and didn't contain too many stones.

The two other enclosures needed additional sand because the sand contained many stones. The additional sand was collected on the border of surrounding roads. A layer of two to three centimetres of loose sand covered the strips.

Figure 2: Sampling strip of 8x3 metres (24m²). It is possible to prepare three walking lines on one strip.

Trail sampling

Trails were sampled in the mornings of March and April 2022. One line of approximately 1 metre large was prepared on the sampling strip by humidifying and raking the sand. The cheetah was then walking along this strip by being lured with a bucket of meat. The trail was first sampled using a drone (Parrot Anafi with a Sony optical sensor 1/2.4'' CMOS, an ASPH lens (Low-dispersion aspherical lens) and a focal length of 23-69mm). Three scale bars and one angular ruler with five photogrammetric targets were placed in each corner of the trail to help scaling the 3D model and to improve precision. Approximately 20 pictures per trail were taken manually by flying at 2 metres high along the trail in opposite directions. After aerial photogrammetry, terrestrial photogrammetry was carried out by taking between 55 and 70 pictures starting from the first track and walking all around the trail in one direction and then turning back around the trail in the opposite direction. Three pictures of the whole trail were taken from the beginning and from the end. A Nikon D500 camera (with a 20-megapixel APS-C sensor and equipped with a Nikkor 18-105mm f/3.5-5.6G lens) was used to sample the trails. Direct measurements were then performed using a foldable metre. Paces, strides front and strides hind were measured for each trail. The pace is the distance between one front track and one hind track directly following each other and belonging to the same side of the animal (right or left). The stride is defined as the distance between the two closest tracks made by the same foot.

Track sampling

Tracks were sampled just after the trails. We only sampled the best quality tracks (i.e., the ones with clear main pad and toes). Five pictures of the footprint were taken, one from above and one from each cardinal point at an angle of 45° from the soil (Figure 3). The pictures were taken using the same camera as for the terrestrial photogrammetry. An angular ruler with four photogrammetric targets was placed next to the tracks to facilitate the 3D reconstruction and to enable scaling.

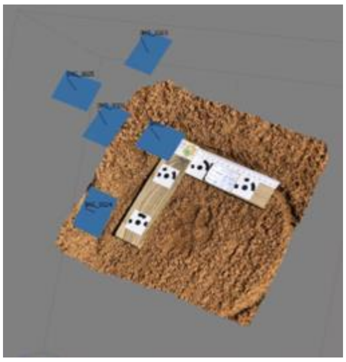


Figure 3: Position of the cameras in space represented by the blue rectangles.

To study the track degradation over time, we selected a subset of tracks that were encircled with stones to protect them from being walked over by the cheetahs.

A few tracks were left unprotected to avoid the bias caused by the stones and evaluate the difference between protected and unprotected tracks in terms of environmental degradation.

3D modelling and landmark positioning

All the pictures were used to make 3D models in the program Metashape Agisoft Professional version 1.8.2 build 14127 (Agisoft LLC, 2022). The main steps to reconstruct a 3D model are the camera alignment, building of the dense cloud, building of the mesh, and building of the texture. These steps were processed automatically for individual tracks and trails sampled with the drone by using a Python script. The reconstruction parameters used to model the tracks were the same as in Baralle et al. (2021).

The trails sampled with the camera were modelled manually. The reconstruction parameters used to model the trails, both with camera and drone, were the same as in Marchal et al. (2017).

All the models were scaled using automatically recognized targets.

The 3D models from the tracks were segmented manually in the program CloudCompare to extract the main pad and four toes from the background. The 3D models were first coloured according to depth to facilitate the visualisation and to limit observer bias during segmentation (Figure 4).

Figure 4: 3D model coloured by depth in CloudCompare.

For further analysis, the tracks were submitted to geometric morphometrics through the use of the geomorph package (version 4.0.4) in R (R version 4.1.3) to extract information about the geometry of the tracks. These methods are based on the positioning of landmarks, which are discrete anatomical loci recognised equally for all the studied specimens (Zelditch *et al.*, 2004) and describe the shape of the specimens (Slice, 2007). Two types of landmarks can be placed on a specimen: fixed landmarks, which are placed manually, and semi-landmarks, which are placed automatically and slide along surfaces and/or curves (Sherratt, 2016). 25 fixed landmarks were first placed on the segmented models according to Jewell et al. (2016) and 130 semi-landmarks were then placed automatically along surfaces using the track closest to the consensus obtained after performing General Procrustes Analysis (explained below) using fixed landmarks as the template.

For the trail models, one landmark was placed on the position of each footprint (between the main pad and the toes). These landmarks are used to calculate the same distances as measured in the field (pace, stride front and stride hind), but digitally.

Data analysis

The 155 landmarks (25 fixed ones and 130 surface sliders) placed on each track were used to perform a General Procrustes Analysis (GPA). This analysis superimposes the landmarks coordinates to a common coordinate system and separates shape from position, orientation, and size (Mitteroecker and Gunz, 2009; Adams and Otárola-Castillo, 2013). The resulting coordinates are named Procrustes coordinates which contain a set of shape variables used for multivariate analysis (Adams and Otárola-Castillo, 2013). A consensus object based on the mean position of the superimposed landmarks comes out of the GPA and will be the comparison element for the set of shape variables (Zelditch *et al.*, 2004). The centroid size of each specimen is calculated during GPA to consider size information. Information resulting from the addition of shape and size variables also emerges from GPA and is called “form”.

The Procrustes coordinates from GPA on 3D fixed landmarks and on 3D fixed landmarks and surface-sliders were used to run a Principal Component Analysis (PCA).

The scores obtained by the variables for each Component were used to make a Linear Discriminant Analysis (LDA) with jack-knife prediction. The Principal Components (PC) were added one by one to compare the accuracy of prediction for each factor (i.e., position, sex, weight, and identity). Another LDA was conducted by combining PC with the centroid size of each specimen to compare prediction accuracy using shape information versus using form (i.e., size + shape) information. For weight prediction, individuals were sorted in four weight categories (i.e., between 30 and 40 kg, between 40 and 50 kg, between 50 and 60 kg and above 60 kg). As females were all part of the same category (i.e., between 30 and 40 kg), weight analysis was also conducted on males only.

Total prediction accuracies were calculated for the entire database (i.e., from 2019 and 2022, n=831) and for separated data sets by foot position with 3D fixed landmarks only and with 3D fixed landmarks combined to surface sliders using (i) one common template and (ii) one template per position.

Total accuracy for each factor was calculated using the following formula from Baralle et al. (2021) for two steps identifications (i.e., divided data sets):

"Total accuracy = Position prediction × ((FL dataset′s prediction + HL dataset′s prediction + FR dataset′s prediction + HR dataset′s prediction)/4)"

When a one template per position data set was used, position prediction occurring in the previous formula was taken from the one common template to calculate total accuracy.

For the trails, the placed landmarks were used to process statistical analyses in R (R version 4.1.3) and the probability values were considered as statistically significant when p-value ≤ 0.05. Direct versus digital measurements (i.e., measurements extracted from both camera- and drone-based 3D models of the trails) coming from 32 trails were plotted with an adjusted linear regression between all measuring techniques. A Spearman’s rank-order correlation test was conducted between every pair of measuring techniques for every type of measurement to analyse correlation between the measuring techniques.

To determine cheetahs gait characteristics, mean pace, stride front and stride hind were calculated for all the cheetahs, for adult females, and for adult males. Females and males means were compared thanks to a Mann-Whitney test for each measure to show the possibility of sex discrimination through gait characteristics.

RESULTS

Identification based on 3D models of tracks

Table 1: Number of tracks per position for each individual and general information about each individual (AF = Adult Female, AM = Adult Male; FL = Front Left, HL = Hind Left, FR = Front Right and HR = Hind Right).

Cheetah	Sex	Age	Weight (2019)	Weight (2022)	FL	HL	FR	HR	Total
AF1	F	Adult	35	31.3	23	37	22	25	107
AF2	F	Adult	31.6	35.4	28	23	28	23	102
AF3	F	Adult	35.4	38	26	24	29	30	109
AF4	F	Adult	37.4	38.5	21	27	23	26	97
AM1	M	Adult	55.2	60.8	31	31	25	27	114
AM2	M	Adult	52.3	51.7	24	24	25	24	97
AM3	M	Adult	54.3	52.8	25	25	22	23	95
AM4	M	Adult	45.1	46	24	28	25	33	110
Total					202	219	199	211	831

A total of 831 tracks were used to determine position, identity, sex, and weight of the eight semi-captive studied cheetahs (Table 1). This database resulted from the merging of 669 tracks sampled in 2019 (Baralle *et al.*, 2021) and 162 tracks sampled in 2022.

The PCA showed that PC1 and PC2 explained between 38.96% and 7.78% and between 14.82% and 5.88% of the variation respectively when considering all the case studies. Using all the tracks from the combined database (i.e., from 2019 and 2022) explained more variation than using only tracks from one position. However, visualisation of the PCA coloured by positions revealed the interest of separating the data set as a strong discrimination in foot positions appears (Figure 5).

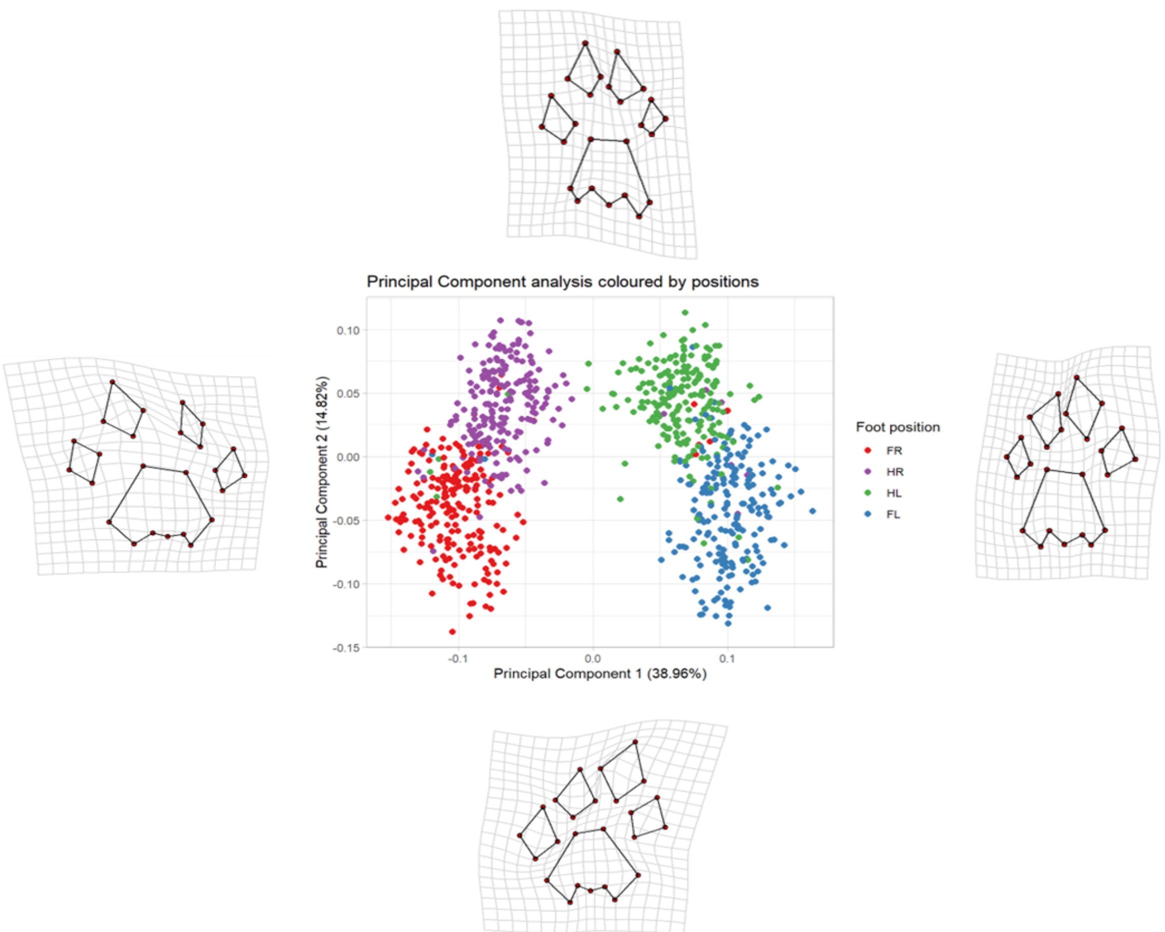


Figure 5: Principal Component Analysis (PCA) of combined database from 2019 and 2022 (n=831) with fixed landmarks only in 3D and form information coloured by the position of the track (FR = Front Right, HR = Hind Right, FL = Front Left and HL = Hind Left). The thin-plate spline deformation grids illustrate the difference in shape between the tracks corresponding to the extremes of each principal component axis and the consensus.

Separated data sets allow other factors (i.e., identity, sex, and weight) to be more clearly distinguished. Individual discrimination is observed but is stronger for some characteristic individuals (Figure 6), sex distinction is evident (Figure 7), and weight differentiation is observable although it is less clear (Figure 8). Better weight discrimination was obtained by only analysing males (Figure 9).

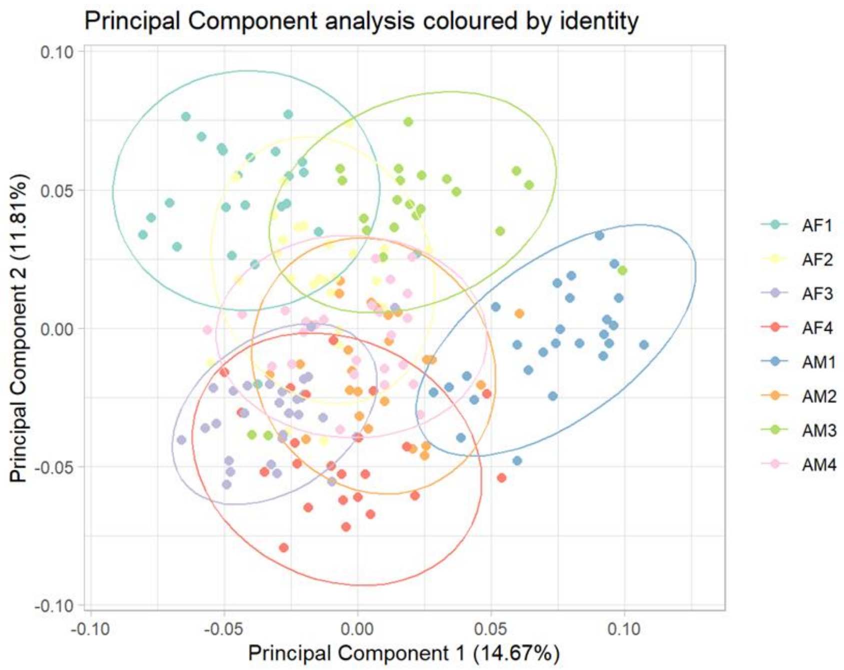


Figure 6: Principal Component Analysis (PCA) of Front Right (FR) tracks from combined database from 2019 and 2022 (n=202) with fixed landmarks only in 3D and form information coloured by the identity of the cheetah that produced the track (AF1 = Adult Female 1; AF2 = Adult Female 2; AF3 = Adult Female 3, AF4 = Adult Female 4; AM1 = Adult Male 1; AM2 = Adult Male 2; AM3 = Adult Male 3; AM4 = Adult Male 4).

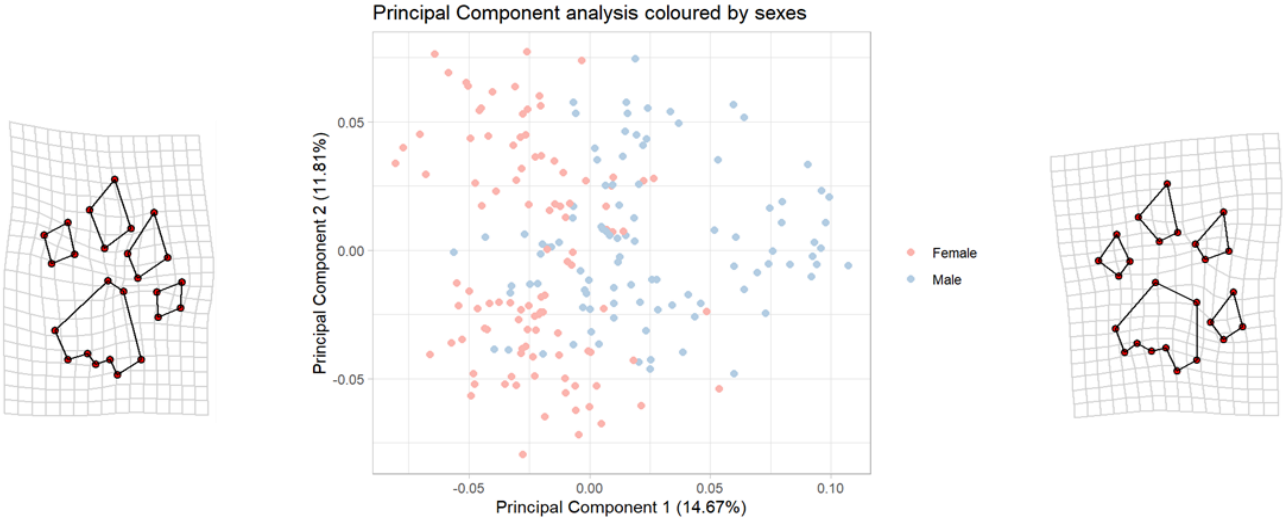


Figure 7: Principal Component Analysis (PCA) of Front Right (FR) tracks from combined database from 2019 and 2022 (n=202) with fixed landmarks only in 3D and form information coloured by the sex of the cheetah that produced the track. The thin-plate spline deformation grids illustrate the difference in shape between the tracks corresponding to the extremes of the first principal component axis and the consensus.

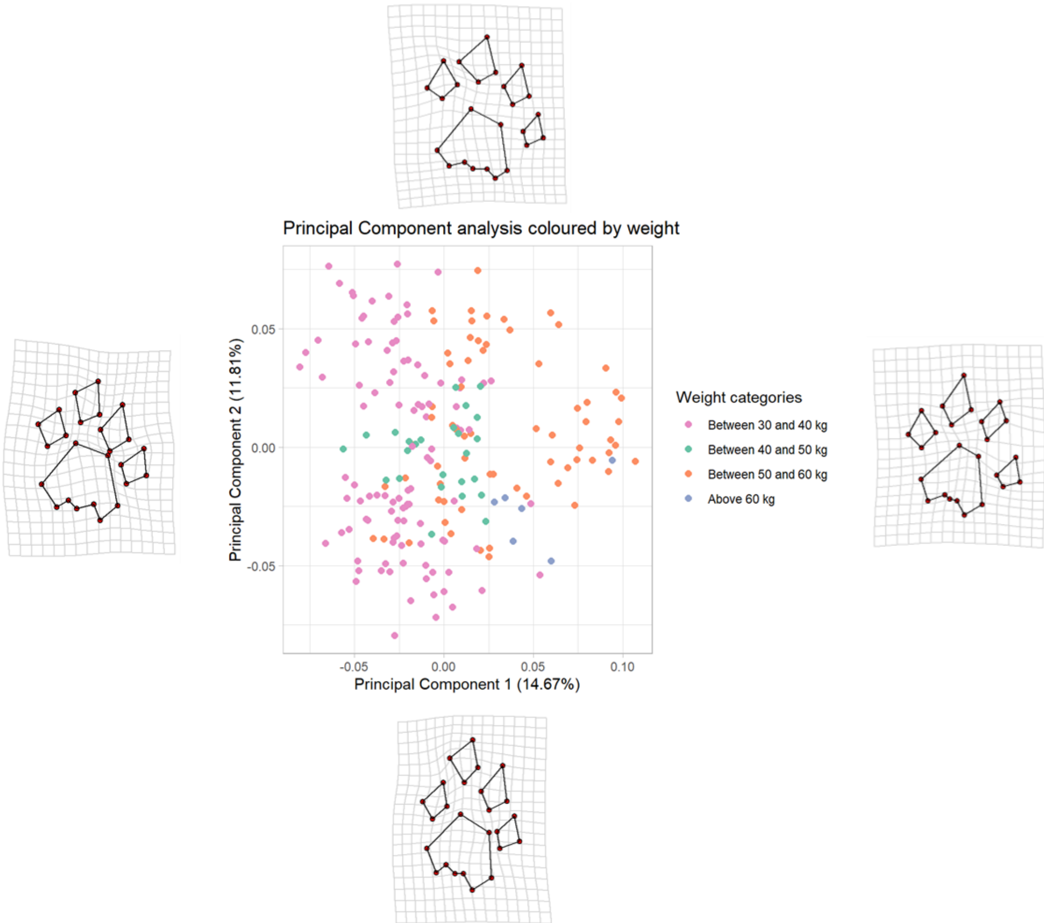


Figure 8: Principal Component Analysis (PCA) of Front Right (FR) tracks from combined database from 2019 and 2022 (n=202) with fixed landmarks only in 3D and form information coloured by the category of weight of the cheetah that produced the track. The thin-plate spline deformation grids illustrate the difference in shape between the tracks corresponding to the extremes of each principal component axis and the consensus.

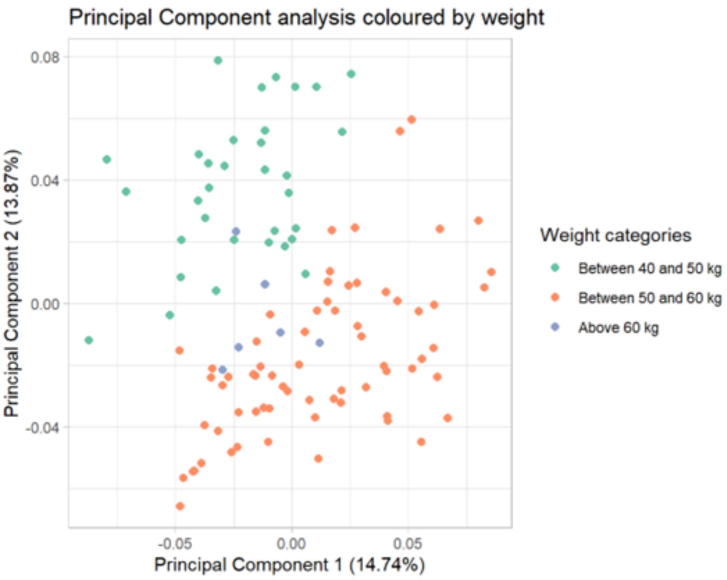


Figure 9: Principal Component analysis (PCA) of Hind Right (HR) tracks from males from combined database (i.e., 2019 and 2022, n = 106) with fixed landmarks only in 3D and form information coloured by the category of weight of the cheetah that produced the track.

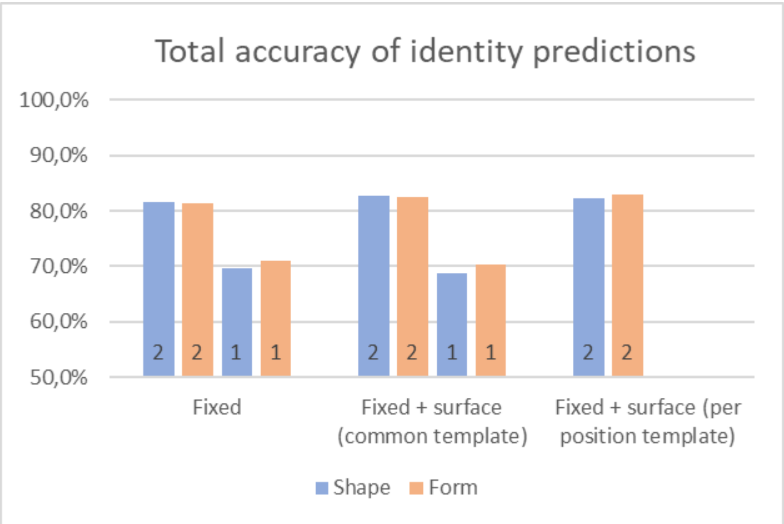
The LDA has estimated the maximum prediction accuracy for each studied category (i.e., complete data set or position-separated data set and fixed landmarks or fixed and surface sliders). The accuracy percentage was obtained by selecting the maximum prediction met with the less PC implemented inside the LDA. Separate data sets assessed better predictions than complete database for identity, sex, and weight (Table 2). The best total accuracy for identity prediction (82.9%) was encountered using 3D fixed landmarks and surface sliders from one template per position while studying form (Figure 10 A.). As to the best total accuracy for sex prediction (87.9%), it was encountered using 3D fixed landmarks with surface sliders from one common template while studying the form (Figure 10 B.). As for the best accuracy for weight prediction (87.6%), it was encountered in the same conditions as the best total accuracy for sex prediction (Figure 10 C.). The best total accuracy does not differ much regarding the template used; 0.5% for identity, 0.04% for sex, and 1.3% for weight.

Two steps identification proved to be more accurate for overall predictions for each factor (i.e., identity, sex, and weight). Besides, there are lower differences in shape and form studies. The mean differences are 0.83% for identity predictions, 1.36% for sex predictions and 1.08% for weight predictions.

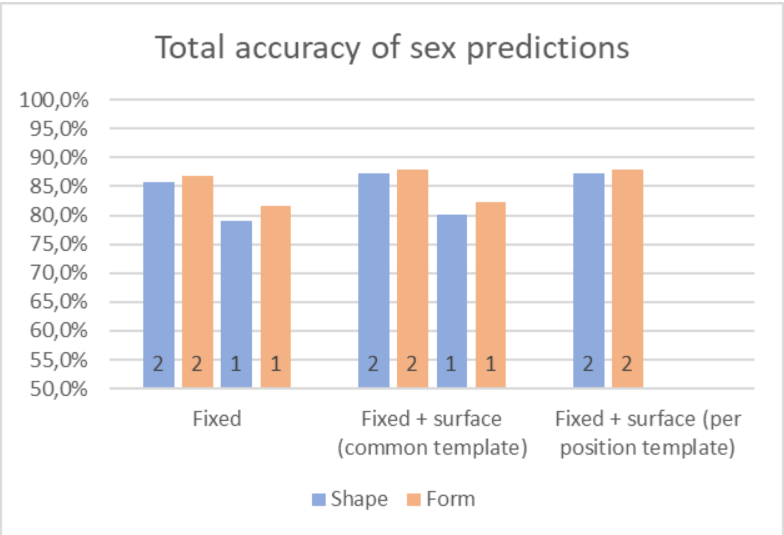
Table 2: Maximum prediction accuracy obtained for each combination and each factor using combined database from 2019 and 2022 (n=831).

Landmarks configuration		Fixed		Fixed + surface sliders (one common template)		Fixed + surface sliders (one template per position)	
Tracks used (n)	**Factor**	Shape	Form	Shape	Form	Shape	Form
All (831)	pos	93,38%	93,14%	95,19%	95,07%	-	-
	id	69,55%	71,00%	68,71%	70,28%	-	-
	sex	80,02%	82,67%	80,39%	82,79%	-	-
	weight	77,74%	79,66%	76,77%	79,06%	-	-
FL (202)	id	82,18%	82,18%	80,60%	79,60%	82,67%	83,17%
	sex	93,07%	94,55%	91,04%	93,03%	91,58%	93,56%
	weight	90,10%	90,59%	88,56%	89,55%	87,62%	89,11%
FR (202)	id	90,59%	90,59%	92,57%	92,57%	91,09%	91,09%
	sex	98,02%	98,51%	98,02%	98,51%	97,52%	98,51%
	weight	93,56%	95,05%	94,06%	95,54%	93,07%	94,55%
HL (217)	id	87,56%	88,02%	86,18%	87,10%	86,64%	86,18%
	sex	88,02%	89,40%	90,32%	89,40%	88,94%	88,48%
	weight	90,32%	89,86%	92,17%	92,17%	88,94%	88,48%
HR (210)	id	89,52%	89,05%	88,57%	88,10%	85,24%	88,57%
	sex	88,10%	90,00%	87,62%	89,05%	89,05%	89,05%
	weight	93,33%	94,29%	91,90%	91,43%	91,43%	91,43%

A.



B.



C.

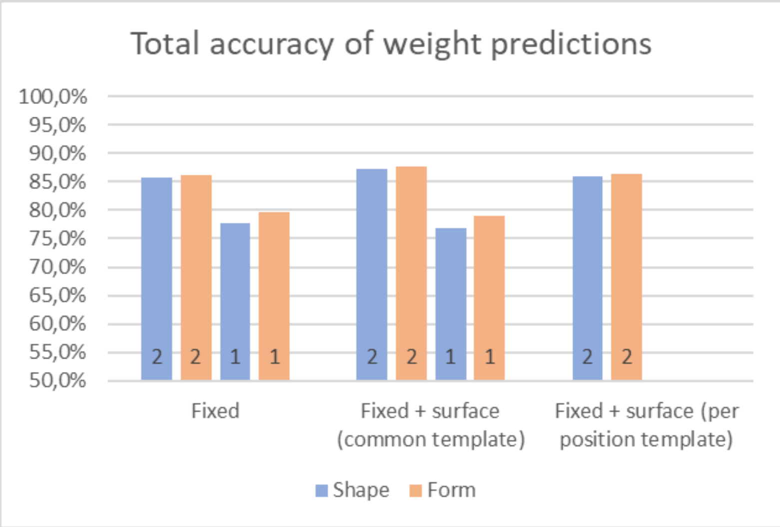


Figure 10: A. Total accuracy for identity prediction for combined database (i.e., from 2019 and 2022; n=831). Numbers inside the bars correspond to the number of identification steps in the combination. "1" corresponds to all the tracks used directly for the prediction, "2" corresponds to position prediction for the entire track set combined to identity prediction with data sets already divided by position (i.e., two identification steps: first is position and second is identity).

B. Total accuracy for sex prediction for combined database (i.e., from 2019 and 2022; n=831). Numbers inside the bars correspond to the number of identification steps in the combination. "1" corresponds to all the tracks used directly for the prediction, "2" corresponds to position prediction for the entire track set combined to sex prediction with data sets already divided by position (i.e., two identification steps: first is position and second is sex).

C. Total accuracy for weight prediction for combined database (i.e., from 2019 and 2022; n=831). Numbers inside the bars correspond to the number of identification steps in the combination. "1" corresponds to all the tracks used directly for the prediction, "2" corresponds to position prediction for the entire track set combined to weight prediction with data sets already divided by position (i.e., two identification steps: first is position and second is weight).

Accuracy predictions for weight were improved by using the data sets from males only (Table 3). Only three weight categories were represented within the males database (i.e., between 40 and 50 kg, between 50 and 60 kg and above 60kg). The best accuracy prediction (100%) was obtained for Hind Right (HR) data set using 3D fixed landmarks only while studying shape and form (Table 3).

Table 3: Maximum prediction accuracy obtained for each combination and each factor using males from combined database from 2019 and 2022 (n=416).

Landmarks configuration		Fixed		Fixed + surface sliders (one common template)		Fixed + surface sliders (one template per position)	
Tracks used (n)	**Factor**	Shape	Form	Shape	Form	Shape	Form
All (416)	weight	91,35%	91,11%	90,63%	90,38%	-	-
FL (104)	weight	93,27%	93,27%	92,31%	93,27%	93,27%	93,27%
FR (98)	weight	92,86%	91,84%	90,82%	91,84%	93,88%	93,88%
HL (108)	weight	95,37%	96,30%	99,07%	99,07%	96,30%	98,15%
HR (106)	weight	100,00%	100,00%	97,17%	97,17%	98,11%	98,11%

The degradation study showed mixed results. Position prediction stays regular over the sampled days, even if there is a slight decrease for sampling up to 48 hours later using 3D fixed landmarks combined with surface sliders (Figure 11). Curiously, prediction accuracy for identity tends to increase with time while using 3D fixed landmarks only (Figure 11). Sex and weight prediction accuracies increase when sampling the track several hours later but then drops down with time (Figure 11).

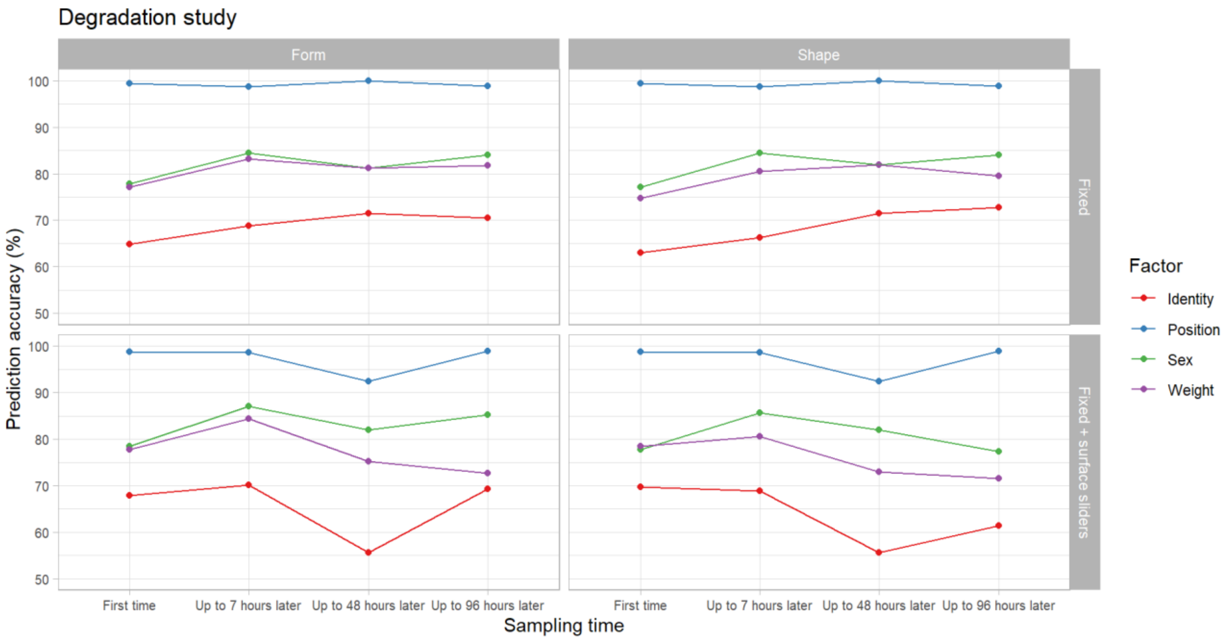


Figure 11: Maximum prediction accuracy obtained for each degradation data set using 2022 database (n=467) over 96 hours.

Trail measuring technique

A total of 32 trails were used to compare the three measuring techniques (i.e., direct, camera and drone) (Table 4). The relation between all three measures showed to be almost perfectly linear with a regression coefficient equal to 0,97 (Figure 12). The Spearman's rank-order correlation test illustrates the better approximation of direct measurements by the drone measuring technique than the camera measuring technique for each type of measurement (Table 5). Indeed, a correlation of 0,97 was obtained between direct and drone measurements for each category against 0,97 for pace, 0,93 for stride front and 0,94 for stride hind between direct and camera measurements (Table 5).

Table 5: Details of the 32 cheetah trails used for the trail measuring technique and sampled in Naankuse in 2022. A track set includes the 2 tracks made by front and hind feet from the same side and within the same walking cycle. Overstep designates a way of walking when hind foot touches down beyond front foot.

Cheetah ID	Trail ID	Gait	Sex	Age	Number of tracks	Number of track sets	Number of pictures (terrestrial)	Number of pictures (aerial)
AF1	3	Overstep	F	Adult	28	14	61	25
AM1	5	Overstep	M	Adult	25	12	57	23
AM1	7	Overstep	M	Adult	24	12	55	22
AF1	8	Overstep	F	Adult	28	14	58	25
AM2	28	Overstep	M	Adult	24	12	60	18
AM3	30	Overstep	M	Adult	26	13	62	19
AM3	31	Overstep	M	Adult	27	13	59	20
AM2	32	Overstep	M	Adult	25	12	58	18
AM2	33	Overstep	M	Adult	27	13	61	19
AM2	35	Overstep	M	Adult	24	12	58	20
AM2	36	Overstep	M	Adult	26	13	62	18
AM3	37	Overstep	M	Adult	25	12	62	19
AM2	38	Overstep	M	Adult	25	12	63	18
AF2	47	Overstep	F	Adult	27	13	64	16
AM1	48	Overstep	M	Adult	26	13	68	19
AF3	49	Overstep	F	Adult	30	15	72	19
AM4	50	Overstep	M	Adult	29	14	68	19
AF3	54	Overstep	F	Adult	30	15	65	21
AM4	56	Overstep	M	Adult	27	13	64	17
AM4	57	Overstep	M	Adult	28	14	65	16
AM4	60	Overstep	M	Adult	29	14	69	15
AF4	61	Overstep	F	Adult	28	14	69	17
AF4	64	Overstep	F	Adult	29	14	68	17
AM4	65	Overstep	M	Adult	27	13	69	17
AM4	66	Overstep	M	Adult	29	14	71	18
AF3	67	Overstep	F	Adult	29	14	67	16
AF4	68	Overstep	F	Adult	28	14	65	14
AF3	69	Overstep	F	Adult	30	15	74	16
AF4	70	Overstep	F	Adult	26	13	73	17
AF3	71	Overstep	F	Adult	30	15	67	16
AF4	73	Overstep	F	Adult	29	14	73	17
AF4	74	Overstep	F	Adult	30	15	76	17

Table 6: Spearman's rank-order correlation test coefficients between every combination of direct, camera and drone measurements.

Type of measurement	Correlation between direct and camera measurements	Correlation between direct and drone measurements	Correlation between camera and drone measurements
Pace	0,977479007	0,979552388	0,992943614
Stride front	0,933526549	0,970831219	0,939207485
Stride hind	0,94920868	0,975909665	0,956020019

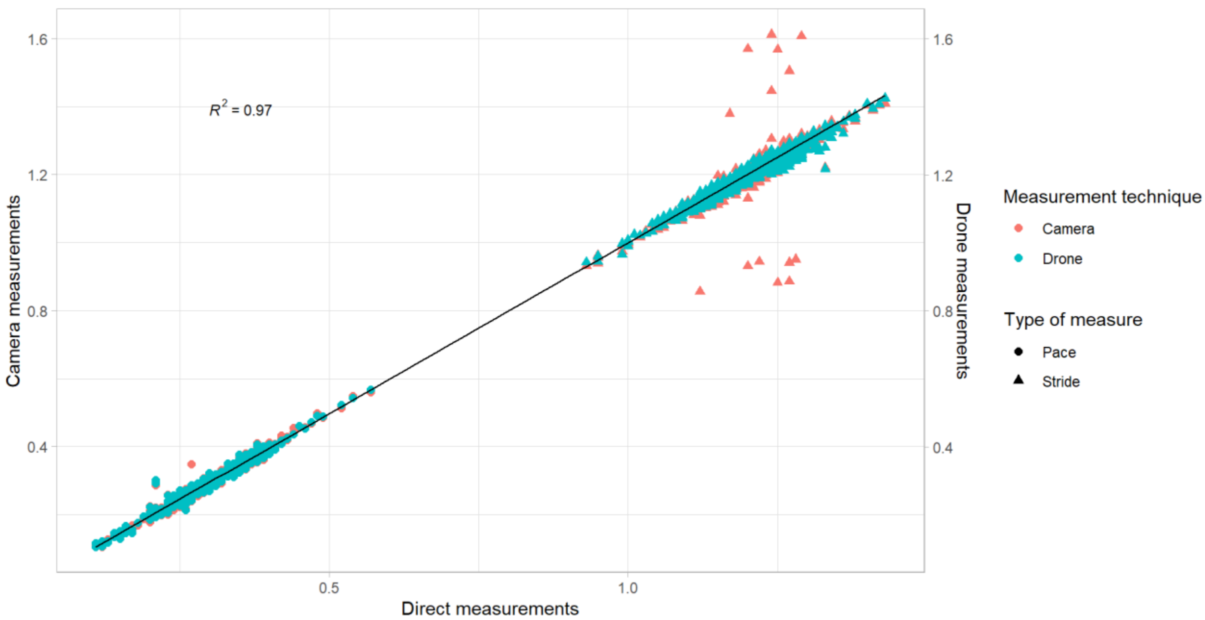


Figure 12: Regression of direct versus digital measurements (camera and drone). Colour code indicates the used measurement technique. The line represents the linear regression between all three techniques and R² is the regression coefficient. The shapes highlight the type of measure. The measurements were taken on cheetah trails in Naankuse (Namibia) from 8th of March to 30th of April 2022.

Pace, Stride front and Stride hind

The mean pace was 31.54 ± 0.49 cm, the mean stride front was 122.38 ± 0.49 cm, and the mean stride hind was 122.33 ± 0.51 cm for all individuals. For females, the mean pace was 29.85 ± 0.64 cm, the mean stride front was 119.94 ± 0.69 cm, and the mean stride hind was 119.70 ± 0.71 cm. And, for males it was 32.93 ± 0.70 cm, 124.39 ± 0.63 cm, and 124.53 ± 0.67 cm respectively. All gaits were considered as similar as they were qualified as "overstep".

The differences between overstepping males and females in pace, stride front and stride hind were all statistically significant (Mann-Whitney test: W = 45929, p-value = 3.924e-10 (<0.05) for Pace, W = 39412, p-value < 2.2e-16 (<0.05) for Stride Front and W = 38019, p-value = < 2.2e-16 for Stride Hind). This implies that cheetah males walk differently than cheetah females at same gait meaning that trails information could probably contribute to sex discrimination using LDA.

DISCUSSION AND CONCLUSION

Identification based on 3D models of tracks

The high accuracy of position identification (over 93%) using complete database (i.e. from 2019 and 2022, n = 831) encourages the splitting by position (Table 2). This two-step identification technique allows to increase identity, sex and weight predictions which remain imprecise when using complete database (i.e., from 2019 and 2022, n = 831) (Figure 10). A likely explanation to this poor identification is the morphology differences between tracks. Indeed, the size of each pad differ depending on the right-left symmetry and the length of the impression of the paw on the substrate (Baralle *et al.*, 2021). Cheetahs have wider front paws and longer hind paws which are perceived with difficulty while performing PCA. Right and Left separation is, however, more efficient (Figure 5).

Weight categories were successfully assessed when studying male tracks only. As females were all part of the same weight category, it didn't make sense to include them in the weight analysis. The prediction reached more than 90% for each tested data set. Adult cheetahs weigh between 20 and 70 kg in general (Marker, 2002). The studied cheetahs ranged from 30 to a bit more than 60 kg. It was decided to group cheetahs in categories of 10 kg but it would be interesting to evaluate the possibility of improving precision in weight identification by reducing the range of every category.

Deformations of the tracks can occur when the substrate is not ideal (Milàn, 2006). Thus, when the sand is too soft and dry, the track elongation can be more important due to weight transfer from the animal on its leg while moving (Baralle *et al.*, 2021). This happens more to front tracks, making them look like hind ones. Furthermore, soft and dry sand can also bring particles inside the track reducing quality and lead to poorly defined edges. This phenomenon was mainly observed on lower parts of the main pad which were often indistinct. The consequences of deformation and poor quality of the tracks are difficulties for segmentation and hence for landmark positioning which are subject to manipulator bias even when colouring 3D models by depth. One manipulator realised the whole segmentation and landmark positioning process to prevent more bias.

Cheetahs also present sexual dimorphism with larger males than females (Marker, 2002; Schmidt-Küntzel *et al.*, 2018). When conditions are not optimal, front feet from males can be mistaken for hind feet from females (Figure 7). Differences in front and hind feet are less pronounced for females because the elongation difference is weak.

This study was conducted in optimal and controlled conditions with high quality sand that was prepared beforehand to stamp clear footprints. In natural conditions, it will be much harder to obtain clear footprints because an ideal substrate (moist, not too deep and smooth) is not frequently encountered, and footprints are prone to quick degradation due to weather, substrate, and the animal's gait. The effect of degradation was studied in this research and showed a decrease in identity, sex and weight predictions in time when using 3D fixed landmarks and surface sliders (Figure 11). When using 3D fixed landmarks only identity predictions tend to increase slightly in time which might be due to the fact that the remarkable extrema of the tracks remained clear while the surfaces and edges became blurry (Figure 11). This means that adding surface sliders to old tracks seems irrelevant as it is not adding information but creating imprecision. However, the tracks were only subjected to environmental degradation (e.g., rain or wind) as they were protected by stones to overcome destruction by the cheetahs inside the enclosure. Therefore, there is a bias on the degradation effect compared to conditions in the wild making it difficult to draw a conclusion on when a footprint becomes too old to be used for identification.

As this identification technique aims to be used in the wild, it would be interesting to test different substrates and gaits to observe the impact on the identification of identity, sex, and weight. A degradation study in the wild would also determine when a footprint becomes too old to produce adequate identification. It would also introduce a perspective on the development of a degradation identification tool to identify how old a found track is. This can be very interesting in the wild to evaluate animal movements and area preferences.

The entire database was separated into four data sets corresponding to each foot position to prevent the position variability. Prediction accuracies increased for every factor because variability between tracks from the same foot position highlighted other information linked to other factors such as identity, sex, and weight. As shown by Baralle et al. (2021), the influence of the used templates to define surface sliders is insignificant. It could show larger differences if a higher number of individuals are used.

Results were not as optimistic as in Baralle et al. (2021) with predictions reaching lower percentages but main trends were observed. The tracks were sampled using a smartphone (Iphone 8) which could lead to less precision than camera sampling although scaling effects are supposed to be removed after GPA. The combination of both databases might also have induced noise as the cheetahs evolved between 2019 and 2022. Observer bias is also multiplied as two different manipulators realised segmentation and landmark positioning.

Curve sliders could also have been added but as 3D models are composed of a polygonal mesh, edges are not smoothed, and this additional information could lead to statistical noise (Baralle *et al.*, 2021). Nevertheless, the impact of combining curve sliders to 3D fixed landmarks and surface sliders on the identification would be interesting to assess to confirm this hypothesis.

The PC1 and PC2 graphs of Front Right (FR) tracks (n=202), show that some individuals are more distinguishable than others (Figure 6). These individuals present noticeable characteristics (e.g., AM1 is the largest cheetah of this database, and his tracks appear as a cluster). Some tracks are overlaid on each other (e.g., AF3 tracks get mixed up with AF4 tracks) and it appears that these tracks belong to related individuals for two of the three groups of cheetahs from the same litter which means it is possible that the morphology of a cheetah is part of the genetics of the species and can be hereditary.

Using shape and form information inside the LDA demonstrated similar results (Table 2, Figure 10). It is explained by the fact that all the studied individuals were adults. Size will show a greater impact if individuals belong to different development stages (i.e., juvenile, adolescent, adult). It is necessary to test the identification technique on more individuals to confirm prediction accuracy. The FIT approach used 38 individuals and obtained a success identification rate of more than 90% (Jewell *et al.*, 2016) despite using only Hind Left (HL) tracks. The advantage of the studied technique is to be able to identify individuals based on any cheetah track and include depth information.

The use of 3D models for track-based identification is time-consuming (Marchal, Lejeune and Bruyn, 2016; Marchal, Lejeune and De, 2017; Baralle *et al.*, 2021). The reconstruction of 3D models is automatic but takes a long time for large databases. This time can be reduced by using professional material like a powerful computer. Segmentation of the 3D models is done manually but it could be automated using a machine learning approach to separate the track from the substrate by making use of depth information (O’Mahony *et al.*, 2020).

However, it would require a large homogeneous database to implement such an approach. This technique has already been considered for 2.5D by FIT and is still in development because it is not really successful yet (Lokare *et al.*, 2014). Furthermore, the placement of 3D fixed landmarks could also be automated by developing an algorithm capable of recognising the extrema of curves from each element of a track.

Trail measuring technique

The three tested measuring techniques turned out to be similar. This means direct measurements are not necessarily needed anymore as digital measurements can replace them. An emphasis is put on pictures acquisition while realising trail studies. Indeed, half of the sampled trails failed to align during 3D modelling because of the lack of object markers around the trail generating very similar pictures only containing sand.

Using a drone to sample trails can replace camera sampling. It allows to cover wider areas and thus longer distances. It preserves the tracks as there is no risk of walking over one of them. The sampling is faster, the image quality is equivalent, and it requires less effort as it is not necessary to walk around the trail. Notwithstanding the advantages of drone sampling, it is also expensive, requires permits to fly legally which can be constraining administratively and is less practically transportable. Anyway, remote sensing represents a huge progress in technology and can become a strong tool for monitoring large carnivores by being safer and offering many sampling possibilities (e.g., drones and satellite images) (Khorram *et al.*, 2012; Xing *et al.*, 2018). However, attention needs to be drawn to the sensitivity of wild animals to Unmanned Aerial Vehicles (UAVs) because these can cause disturbances depending on the animal's character and the type of UAV (Mulero-Pázmány *et al.*, 2017).

As identification of lion (*Panthera leo*) sexes using variables extracted from trails has been proved to be successful (Marchal, 2017), information extracted from cheetah trails (i.e. pace, stride front and stride hind) could be used for the same purpose. It would also be interesting to investigate the possibility of linking information extracted from trails to information extracted from tracks to improve individuals and sex identification. It is likely to succeed as cheetah males and females show differences in gait characteristics.

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