Quantitative discrimination of deformation in Fueguian crania

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Abstract

Objectives: Artificial deformation of the cranium in humans has been related to powerful environmental-cultural stimuli that modify vectors of growth and development when the cranium is still malleable. Osteological differentiation into deformed and nondeformed remains enables the morphological information of individuals that make up ethnic groups or populations to be separately contrasted, the invariant measurements of deformation to be identified, the information provided by archeological remains to be placed in a social context, the cranial variation to be related to genetic variation (individuals without deformation), and predictions to be made (in the absence of direct genetic information).

Methods: With samples of reduced size and many variables, we propose a decision rule based on: (a) pre-selecting variables (Kruskal-Wallis and Λ-Wilks test); (b) applying logistic regression to obtain the optimal classification criterion; and (c) defining a multi-criterion decision rule to bring about greater robustness.

Results: After applying the decision rule to a sample of 180 crania (71 from the Selknam, 74 from the Yamana, and 35 from the Alakaluf ethnic groups), it was possible to identify the Selknam men with frontal deformation and the Yamana women with flattening of the parietal regions at the height of the bregma.

Conclusions: From there on with the information provided by the graphical representation of the populations in the most informative dimensions and the homogeneity contrast between sexes, we related the frontal deformation in Selknam men to dragging firewood, vegetable matter, domestic utensils, and heavy pieces of meat from the hunt. On the other hand, the flattening of the parietal areas at the height of the bregma in Yamana women is related to loading and transporting vegetables and animals in baskets or leather sacks.

KEYWORDS
deformed skulls, Fuego-Patagonians, logistic regression

1 | INTRODUCTION

Cranial-facial growth and development is an integrated process by which regions of different embryonic origin are morpho-genetically and functionally related to make up the structures of the face and cranium. In individuals that have undergone artificial cranial deformation, a powerful environmental-cultural stimulus has modified these patterns of growth and development through compressive forces. When the bones have still not fused (in the first years of life), modification of such patterns leads to permanent changes in the shape of the cranium in the three spatial directions: antero-posterior, transversal, and longitudinal (Lieberman, Pearson, & Mowbray, 2000; Montes & Moreno, 2015; Özbek, 2001). Although it is not known when this practice commenced, the deformation of crania in humans has been widely documented over time and in five continents (Dingwall, 1931). Dated to the Proto-Neolithic and Neolithic periods (9000-8000 BCE), the first traces were found in south-east Asia and Europe (Lorentz, 2010; Meiklejohn, Agelarakis, Akkermans, Smith, & Solecki, 1992). Anthropological remains, both bones and cultural (pictorial and sculpture) were subsequently observed in Ancient Egypt and central Africa, Europe, Near East and India, Oceania, North America, Central America and South America (Buikstra & Ubelaker, 1994; Dembo & Imbelloni, 1938; Özbek, 2001; Ubelaker, 1984; Weiss, 1961).

Artificial deformations come about as a result of practices that may be intentional or unintentional. Intentional modifications are made in order to change the final shape of the cranial vault, while unintentional modifications are produced in a secondary manner as a result of another activity. In general terms, intentional deformation of the cranium is achieved with massages, rigid devices, molds, bandages, and pressure bands (Allison, Gerszten, Munizaga, Santoro, & Focacci, 1981). This intentional molding of the head has been related to cosmetics/esthetics, culture/religion, belonging to a social class or tribal identification (intra- and inter-population), etc. On the other hand, unintentional deformation has been related to systems for holding and transporting babies in cradles or frames, with dragging or loading activities assigned to children and youngsters, with postural disorders, and with accidents (Ayer et al., 2010; Brothwell, 1981; Brown, 1981; Buikstra & Ubelaker, 1994; Dembo & Imbelloni, 1938; Gerszten & Gerszten, 1995; Hyades & Deniker, 1891; Tiesler, 2012; Tubbs, Salter, & Oakes, 2006; Ubelaker, 1984). In both cases, identifying the deformation is not necessarily immediate. The differential intensity and inclination in the application of compressive stimuli and the duration of the practice provide heterogeneous results which can appear as a continuum. To characterize the variation of the modified cranial cavity, classification of the deformations has been proposed. Each type of deformation has been related to the instrument or instruments used to produce it, and the deformations or apparatuses have been correlated to the specific anatomy of the cranium (Cocilovo, 1994; Cocilovo, Varela, & O'Brien, 2011; Dembo & Imbelloni, 1938; Munizaga, 1987; Perez, 2007; Soto-Heim, 1987; Stewart & Newman, 1963; Tiesler, 2013; Weiss, 1961). Additionally, cranial deformation has been related to natural or artificial post-mortem interventions (Del Papa et al., 2011; Guichón & Suby, 2011; Martinez, Flensborg, & Bayala, 2012). On the other hand, morphologies of the cranial vault and face similar to those observed in artificial deformation have also been related to the retention of some ancestral genetic characteristics, and with natural selection as a response to stress caused by extreme environmental conditions (Hernández, Lalueza-Fox, & Garcia-Moro, 1997; Lahr, 1995).

In South America, the bio-archeological record is characterized by wide diversity and a large number of individuals with cranial deformation. Individuals with artificial deformation are concentrated mostly in three areas of the sub-continent (north-west, central-west, and south). Classical references set forward the idea that the greatest morphological variation is in the central-west area, coinciding with chieftainships/states of Andean farmers and shepherds. In this area deformations of the tabular erect, tabular oblique, annular erect, and a sizeable number of intermediate patterns have been documented. Generally speaking, these deformations have been related to intentional modifications (Blom, 2005; Cocilovo et al., 2011; Dembo & Imbelloni, 1938; Dingwall, 1931; Hoshower, Buikstra, Goldstein, & Webster, 1995; Imbelloni, 1933; Perez, 2007; Tiesler, 2012; Torres-Rouff, 2002). In the adjacent areas, north-west (Venezuela and Colombia) and south (Pampa and Patagonia), morphological variations with less diversity have been reported, coinciding with less structured social and political organizations. In the north-west area, cranial deformations have mainly been related to intentional modifications. In the south area, cranial deformations have been related to intentional modifications, unintentional functional modifications, and to post-mortem modifications (Alfonso-Durruty, Giles, Misarti, San Roman, & Morello, 2015; Berón & Baffi, 2003; Guichón, 2002; Kristiansen, 2005; Rodríguez, 2007; Schijman, 2005; Whallon, 2011). In the extreme south of the American sub-continent, Tierra de Fuego, intentional and unintentional cranial deformation has been scarcely reported, and, in the few studies where information is available, the percentage of individuals with deformation is lower than the percentage observed in the rest of the southern area (Alfonso-Durruty et al., 2015; Guichón, 2002). Recent studies have related the pattern of variation of the populations of the American sub-continent with the chronological distribution of the studied samples and, in the north-west and central-west areas of the sub-continent, the pattern of variation has also been related to spatial distribution in the directions north-south and coast-mountain (Perez, 2007; Politis & Madrid, 2001; Pucciarelli et al., 2006; Rodríguez, 2007).

Systematic study of the material remains of human life that has disappeared is geared toward describing and understanding the physical changes, and toward reconstructing the life of ancient peoples. In this context, deformed and undeformed skeletal remains provide different and complementary information. Therefore, for each population or ethnic group it is of interest to differentiate the two groups ("deformed" and "undeformed") and manage the information jointly or separately, depending on the objective. By way of example, with treatment (joint or separate) of the information it is possible to: (a) determine the characteristics and the impact of the deformation and identify the constant measurements of the deformation, opposing the metric information from "deformed" and "undeformed" individuals; (b) with discriminant techniques, select the sub-group of invariant measurements that enable sexual dimorphism to be characterized; (c) place the information provided by archeological remains (pictures, sculptures, burials, and funerary remains, etc.) to be placed in a social context; and (d) prevent cultural information corresponding to deformed individuals from being interpreted as biological. On the other hand, with a number of populations or ethnic groups, the quantitative techniques used in analysis (inference/hypothesis testing, reproduction in reduced dimensions,

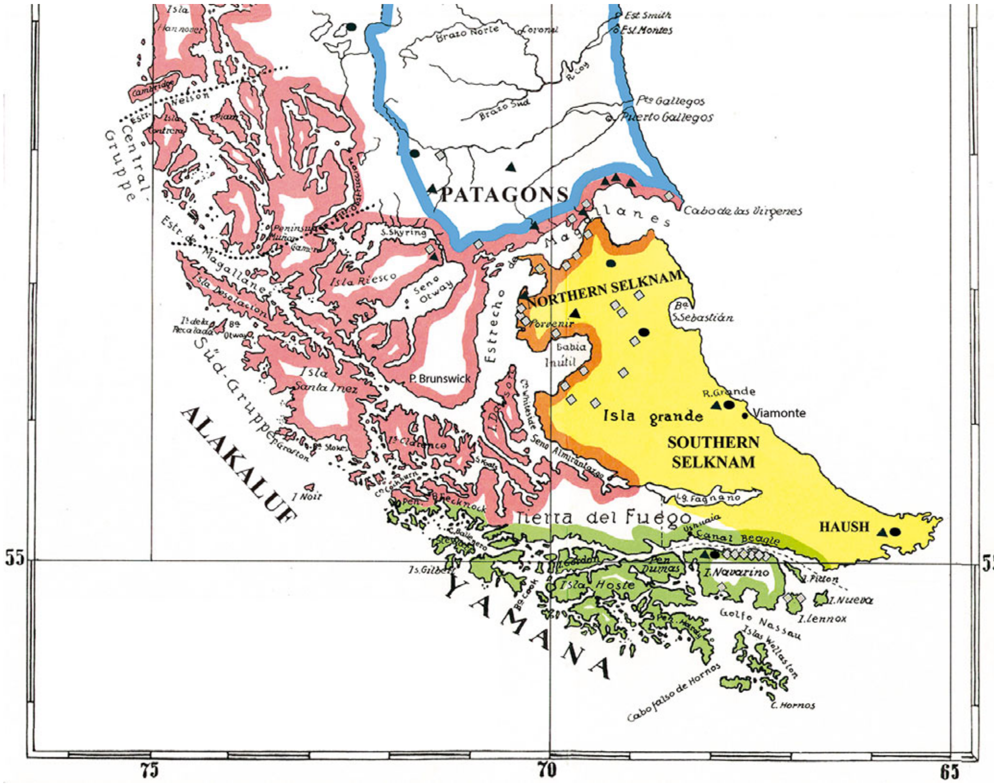

FIGURE 1 Main sites of Tierra del Fuego and South Patagonia showing the diversity of crania, modified or not, by sexes. For more detailed information (only for current Chilean territory), see Alfonso-Durruty et al. (2015). Circles: female; triangle: male. Diamond: Not deformed. In black: with deformation

cluster classification and discriminant analysis, etc.) focus attention on measurements of centralization and dispersion (mean and variance) and, are therefore very sensitive to the presence of atypical data and the inclusion of mixtures of populations (Bormida, 1954; Guha, Rastogi, & Shim, 2000; Hubert, Rousseeuw, & Vanden Branden, 2005; Hubert & Van Driessen, 2004; Perez, 2007; Rhode & Arriaza, 2006).

After recognizing the interest in differentiating the information from osteological remains, attention has focused on achieving reliable discriminators to classify Fueguians into deformed and nondeformed groups. Section 2 describes some aspects of the physical geography of Tierra de Fuego and its inhabitants, the information used in this study is described along with the statistical treatment. In section 3, a multi-criterion decision rule is proposed that permits identification of Selknam men with frontal deformation and Yamana women with flattening of the parietal areas at the height of the bregma. Section 4 discusses the results and presents the conclusions.

2 | MATERIALS AND METHODS

2.1 | Tierra del Fuego: Physical geography and inhabitants

Tierra del Fuego is an archipelago off the southernmost tip of South America. It extends to the south and east of the Strait of Magellan, between the Atlantic and Pacific Oceans, until it reaches Cape Horn. It consists of one main island, Isla Grande, and a huge number of smaller islands that form a complex network of channels (Figure 1). Tierra del Fuego directly receives the cold currents and icy winds from the Antarctic, and rain falls there almost every day. The extreme climatic conditions do not allow the inhabitants of the islands to practice farming or livestock breeding. Despite this, the area is rich in food resources (Estévez & Prieto, 2017; Orquera & Piana, 2009; Prieto, Stern, & Estevez, 2013).

The formation of the Magellan Strait about 10 000 years ago separated Isla Grande from the continent, isolating the island's inhabitants and thus giving rise to the Selknam, an ethnic group that subsisted by hunting. The main source of food was the guanaco, a camelid that was especially abundant on Isla Grande and which was hunted with bow and arrow. The Yamana and Alakaluf on the other hand were hunter-gatherers who used canoes and mainly inhabited the small islands to the west and south of Tierra del Fuego. Both groups exploited the marine resources, mainly seals and shellfish, and seabirds as a secondary resource. The Yamana inhabited the archipelago of Cape Horn, from Bahía Sloggett to the foothills of the Brecknock Peninsula, including the north coast of the Beagle Channel. The territory of the Alakaluf extended from the Brecknock Peninsula to the mouth of the Messier Channel (Figure 1). In both ethnic groups the women were responsible for gathering mollusks, basically the species *mytilus* (Gusinde, 1982 [1931], Gusinde, 1986

[1937], Gusinde, 1989 [1937], Gusinde, 1991 [1974]; Orquera & Piana, 2009).

The records kept by European missionaries in Fueguian territory (end of 19th century and early 20th century) bear witness to the dramatic and progressive extinction of the Fueguians. The disappearance of the descendants of the first inhabitants of South America has been attributed to three factors: displacement of their resources; diseases introduced by Europeans; and the genocide committed by gold prospectors, colonists, and livestock companies. At the end of the war of extermination, the last survivors were taken to the Anglican and Salesian missions in Isla Grande or deported to Isla Dawson. In this period there was also growing interest in preserving the bone material of the Fueguians, since it was believed that they came from a primitive race called the Australoids (Orquera & Piana, 1995). Although not all the Fueguian crania are well documented, a recent study has updated identification of these materials (Turbon, Arenas, & Cuadras, 2017).

2.2 | Data set

The sample consists of 180 modern crania (71 of the Selknam, 74 of the Yamana and 35 of the Alakaluf ethnic groups), from the following European and American collections: Naturhistorisches Museum (Vienna); Istituto di Antropologia (Florence); Università degli Studi *La Sapienza* (Rome); The Natural History Museum (London); Musée de l'Homme (Paris); Museo Etnográfico *J.B. Ambrosetti* (Buenos Aires); Museo de la Plata (Argentina); Museo del Fin del Mundo Ushuaia (Argentina); Misión *La Candelaria*, Río Grande (Argentina); Instituto de la Patagonia, Punta Arenas (Chile); Museo *Mayorino Borgatello*, Punta Arenas (Chile); Museo Provincial de Tierra del Fuego *F. Cordero Rusque*, Porvenir (Chile); Museo *Martin Gusinde* Puerto Williams (Chile); National Natural History Museum (Santiago de Chile); American Museum Natural History (New York) and National Museum Natural History Smithsonian Institution (Washington).

In a first approach, two observers carried out a classification of the crania into three categories ("deformed," "undeformed," and "doubtful"). To identify the frontal deformation, the visual inspection of the craniograms (orthogonal projections of the 180 crania that make up the sample) focused attention on the curvature of the vault, and in particular on the flattening of the frontal area and the lengthening of the occipital zone. In this context, the individuals were classified as "undeformed" when the two observers did not recognize signs of change to the normal shape of the skull. The individuals were classified as "deformed" when the observers detected the presence of obvious signs of alterations to the normal morphology of the cranium. Finally, when the decision was not clear or when there was a disagreement between the observers, the individuals were classified as "doubtful."

TABLE 1 Sample feature: Frontal deformation in Selknam, bregmatic deformation in Yamana and Alakaluf

Ethnic group	*n*	Nondeformed	Deformed	Doubtful
Selknam men	50	16	10	24
Selknam women	21	8	0	13
Yamana men	42	26	2	14
Yamana women	32	16	4	12
Alakaluf men	16	14	0	2
Alakaluf women	19	11	1	7

The inclusion of the numerical indicator, *frontal index* F=FRS/FRC (FRS: frontal subtense; FRC: frontal chord), enabled the classification by consensus carried out by the observers to be corroborated and adjusted. In general terms, the frontal flattening means that the "deformed" individuals present a lower value of F than the "undeformed" individuals. Thus, once the value of F is calculated in the individuals classified in the "deformed" and "undeformed" groups, the following criterion of compatibility and adjustment was applied: (a) the individual was kept in the "undeformed" group when the observed value of F was high and kept in the "deformed" group when the observed value of F was low; and (b) the classification was revised when no compatibility was produced, and, when in doubt, the individual was reassigned to the "doubtful" group.

Similarly, the classification by bregmatic deformation was carried out by the consensus of two observers, but without adjustment with a quantitative indicator. In this case, the visual inspection of the craniograms focused attention on the flattening of the bregma and posterior lengthening of the cranium. With this idea in mind the initial classification (Table 1) made clear that some individuals of the Selknam ethnic group present a frontal deformation (Figure 2) and that some individuals of the Yamana present a bregmatic deformation (Figures 3 and 4). The data base used consisted of 63 variables described in Howells's Craniometric Data Set (Howells, 1973, 1989).

2.3 | Statistical treatment

With an interest in differentiating between deformed and undeformed crania, a two-phase classification was proposed. Phase I, initial classification by consensus of observers (explained in point 2.2) and Phase II, automatic classification using reliable information. To achieve reliability in the initial classification by consensus, the "doubtful" category was introduced. Using the information provided by the individuals initially classified into "deformed" and "undeformed" groups (reliable information of phase I), automatic classification using discriminating methods was proposed. In this context, attention was focused on the "doubtful" group and in particular on reducing its size: some individuals were reassigned to the "deformed" category; other individuals were reassigned to the "undeformed" category; and a few individuals were kept in the "doubtful" group. On the other

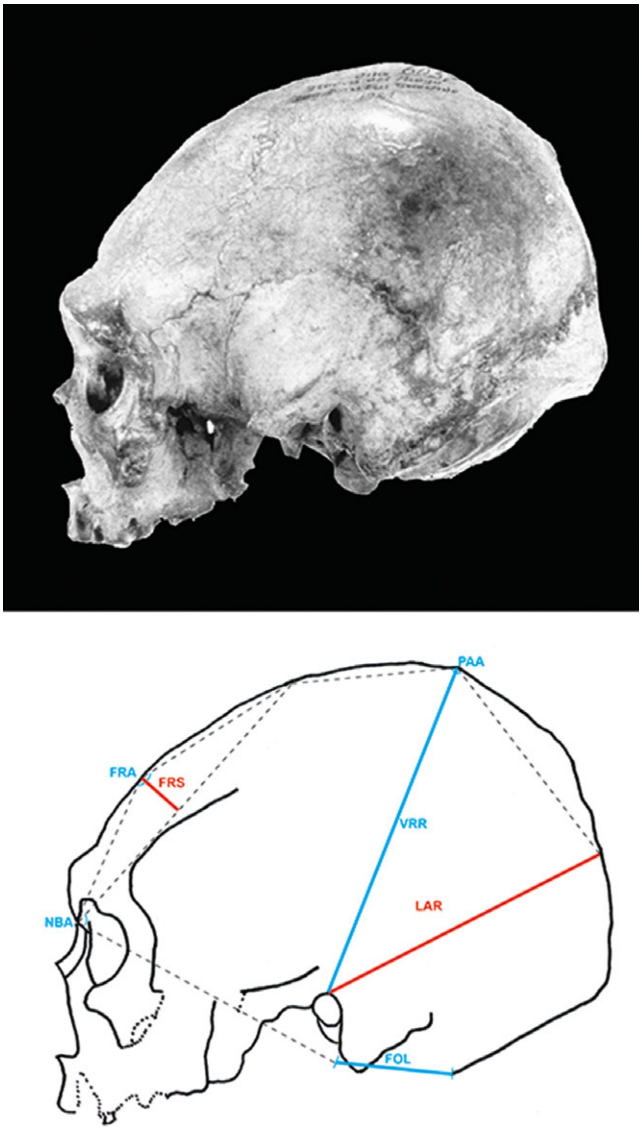

FIGURE 2 Gusinde 7 cranium (6037) from the Natural History Museum of Vienna (Austria), regarded by Gusinde as a "primitive" Selknam for the robustness of the bone and the flattened frontal region. In reality, it is a cranium with frontal deformation. Above: photograph; below orthogonal projection of the G7 showing the most distinctive variables of the deformations of this case: FRS and LAR (red) and other less instrumental ones, such as the segments VRR, FOL and the angles NBA FRA and PAA (Table 2)

hand, the individuals initially classified in the "deformed" and "undeformed" categories kept the allocation in the category.

Given that the main interest was in selecting the most informative variables (Phase II), the ones that presented a greater differential behavior in individuals with and without deformation were identified. For ethnic group and sex, a descriptive analysis was presented (median, SD, and correlation). The Kruskal-Wallis test was used to contrast the medians of the variables and Wilk's Lambda (Λ) was used to evaluate the discriminant power. This statistic relates the internal variability of the groups (deformed and nondeformed) to the total variability (all the individuals). The statistic is expressed in the form:

$$\Lambda = \frac{(n_N-1)\cdot s_N^2+(n_D-1)\cdot s_D^2}{\left[n_N\left(\overline{X}_N-\overline{X}_{N+D}\right)^2+n_D\left(\overline{X}_D-\overline{X}_{N+D}\right)^2\right]+\left[(n_N-1)\cdot s_N^2+(n_D-1)\cdot s_D^2\right]}$$

where $\overline{X}_D, \overline{X}_N$ and $\overline{X}_{D+N}$ are the medians of the variables in the groups (individuals with deformation; individuals without deformation; individuals with and without deformation), and s_D^2, s_N^2, and n_D, n_N are the sample variance and the sample size in each group. Wilk's Lambda statistic varies between 0 and 1: low values are related to high discriminant power and values close to 1 are related to low discriminant power. To favor the reading in percentages, the discriminant power is related to the measurement [1-Λ]·100.

With a binary response (deformed/nondeformed), the logistic regression was used to classify individuals. Logistic regression has several desirable characteristics in the present context: (a) it produces predicted values that can be interpreted as probabilities of group membership; (b) it does not assume a linear relationship between the dependent and independent variables; (c) it does not require multivariate normality of independent variables; (d) it does not assume homoscedasticity; and (e) in general, it has less stringent requirements than linear discriminant analysis (Hosmer, Jovanovic, & Lemeshow, 1989). With a reduced sample size in the reference groups, and especially in the group of individuals with cranial deformation, the prediction models with many explanatory variables are saturated and their reliability is therefore debatable. For this reason, the most informative variables were selected with highly conservative criteria, and with this sub-group of variables the classification criterion was obtained. In particular, the variables that meet the following conditions were selected: (a) the measurement error associated with the resolution of the variable was less than 50% of the difference between the medians of the individuals with and without deformation; and (b) the variable showed significant differences in the Kruskal-Wallis test (P-value <.10) or the discriminatory capacity was higher than 20%

FIGURE 3 Side view of cranium no. 11 of the Yamana canoeist of the collection from the La Sapienza, in Rome (Italy)

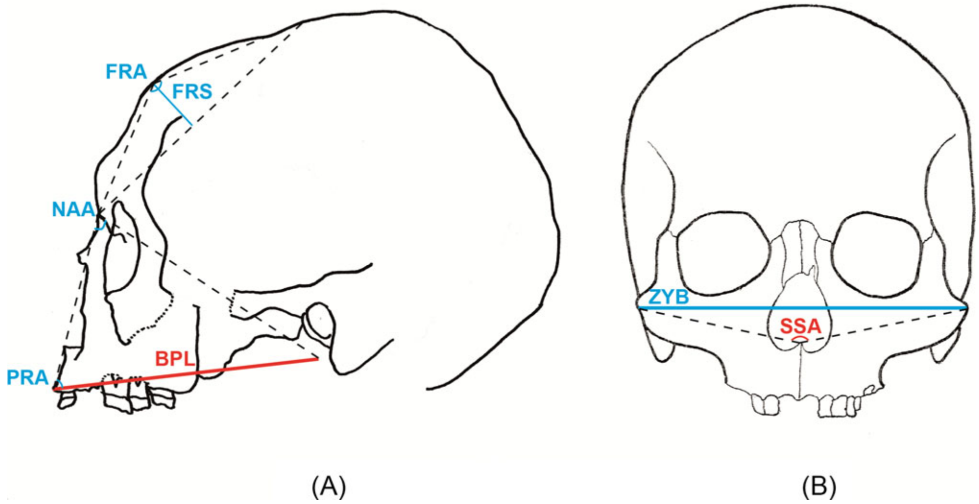

FIGURE 4 Orthogonal projections (lateral and frontal views) of cranium 11 of a Yámana canoeist of the collection from La Sapienza, in Rome (Italy). The two optimal discrimination variables of the BPL and SSA deformation are in red

((1-Λ)·100 > 20). With significant correlations between the explanatory variables and nonsignificance in model coefficients, the prediction model was simplified by using the forward selection criterion. The predictive ability of the classification function was estimated using a leave-one-out method for cross-validation. Besides obtaining the optimal discriminant, other prediction models were also obtained that could provide complementary information, and all the above was used to define a multi-criterion decision rule.

For Selknam men (nine individuals with frontal deformation) the prediction models resulting from including all the sub-groups with two and three variables were obtained, and the most efficient models were chosen. For Yamana women (six individuals with bregmatic deformation) the prediction models made up of groups of two variables were obtained. With the final assignment in the three groups (Phase II), the binomial distribution was used to obtain the sampling uncertainty. This uncertainty is independent of the classification error and was quantified in ±1.96·se = ±1.96·(p·[100—p]/n)$^{1/2}$, where p is the percentage of belonging to the category and n the size of the sample. On the other hand, the chi-squared test was used to contrast homogeneity by ethnic group and sex of the classification.

The prediction models obtained to identify frontal deformation in male Selknams were standardized and applied to individuals of the same sex from other ethnic groups (Yamana and Alakaluf). Likewise, the prediction models obtained to identify the bregmatic deformation in female Yamanas were tested on Selknam and Alakaluf.

3 | RESULTS

The results obtained for men of the Selknam ethnic group showed that the variables with greater capacity to distinguish individuals with frontal deformation were (Table 2): FOL (foramen magnum length: basion–opisthion length), FRS (frontal subtense: nasion-bregma subtense), LAR (lambda radius), VRR (vertex radius), FRA (frontal angle), PAA (parietal angle), and NBA (bregma-nasion-basion angle). Except for the NBA variable, the discriminant capacity was over 20% and the statistical significance of differences between individuals with and without frontal deformation (*P*-value) was less than .10. NBA had a lower discriminant capacity (5.49%) and presented statistical significance in the differences (*P* = .0690). The overlap in the information provided by the variables was evaluated with the correlation coefficient. The two variables with highest discriminant capacity (FRS and FRA) showed a very high negative correlation (ρ[FRS, FRA] = −0.92). The LAR variable (third in discriminant capacity) presented a high correlation with VRR (ρ[LAR, VRR] = 0.75) and a low correlation with the FRS and FRA variables (ρ(LAR, FRS) = −0.10, ρ(LAR, FRA) = 0.20). The PAA variable presented an intermediate correlation with the VRR, FRA and FRS variables (near to 0.5). NBA presented a low correlation with all of the variables, except with con FRA (ρ[NBA, FRA] = −0.31), and FOL had a very low correlation with the other variables (ρ < 0.26 in all cases). The other observed variables (56) had a discriminant capacity under 20% and did not show statistical significance when the Kruskal-Wallis test was applied (*P*-value > .10 without adjustment for multiplicity) or the measurement was not very reliable.

The logistic regression model provided the predictive equation.

$$PF = \frac{e^{\eta}}{1+e^{\eta}} \tag{3.1}$$

where

$$\eta = -753.65 - 27.63 \cdot \mathrm{FRS} + 12.45 \cdot \mathrm{LAR} \tag{3.2}$$

The decision criterion for this predictive equation was based on a value of 0.5 (which allowed the greatest balance

TABLE 2 Selected variables, descriptive statistics and comparison of means for deformed and non-deformed individuals (mean: $\overline{X}$, SD: s, Kruskal-Wallis statistics: KW_{exp}, and Wilks' lambda: Λ)

Selknam (men)	Variable Name	Nondeformed		Deformed		Kruskal-Wallis test		Discrimination	
		$\overline{X}$	s	$\overline{X}$	s	KW_{exp}	*P*-value	Λ	(1 − Λ)·100
	FOL	42.69	4.24	38.10	3.41	6.19	.0128	0.7430	25.70%
	FRS	23.56	2.00	19.95	1.77	12.23	.0005	0.5233	47.67%
	LAR	105.38	3.32	111.11	5.06	7.93	.0049	0.6612	33.88%
	VRR	121.63	3.32	125.90	4.77	5.07	.0243	0.7672	23.28%
	FRA	135.75	2.64	142.19	3.43	13.62	.0002	0.4522	54.78%
	PAA	137.70	4.02	132.37	5.64	5.63	.0177	0.7516	24.84%
	NBA	75.73	1.90	74.53	3.32	3.30	.0690	0.9450	5.49%
Yamana									
(women)	BPL	97.63	3.01	104.50	3.11	7.60	.0058	0.5214	47.86%
	SSA	123.69	4.45	127.50	2.08	3.27	.0701	0.8697	13.03%
	ZYB	130.56	2.99	137.25	4.92	5.25	.0219	0.5909	40.91%
	NAA	69.94	2.98	73.27	3.68	3.22	.0725	0.8309	16.91%
	PRA	69.45	2.02	66.90	1.49	5.14	.0233	0.7657	23.43%
	FRS	23.81	2.14	20.50	0.58	6.23	.0125	0.6642	33.58%
	FRA	131.75	3.64	137.53	1.56	7.00	.0081	0.6587	34.13%
	BNL	97.38	2.44	100.50	2.64	3.66	.0556	0.7799	22.01%
	MDH	23.91	3.10	27.00	2.82	3.44	.0635	0.8463	15.36%
	IML	37.50	4.17	41.00	3.91	2.79	.0947	0.8870	11.29%
	OCF	47.25	5.40	51.25	2.50	3.96	.0464	0.8994	10.06%
	PRR	100.25	3.23	105.00	3.36	4.55	.0327	0.7256	27.43%
	ZMR	71.00	3.44	75.00	1.41	6.65	.0098	0.7823	21.77%
	AVR	80.44	3.89	86.00	1.82	6.82	.0089	0.7061	29.38%
	BRA	47.16	2.02	49.06	0.39	4.52	.0334	0.8430	15.70%

in the probability of an erroneous classification between the two groups). Thus, values of PF over 0.5 were associated with crania with frontal deformation and values under 0.5 for crania without frontal deformation. The application of this prediction model provided an estimate of the probability of correct classification of 100% (in deformed and non-deformed crania). This probability of correct classification is generally related to the predictive capacity of the model. In samples of reduced size (references below 100 individuals in each group: 16 nondeformed and 9 deformed) this ratio requires some explication: the model has a very high predictive capacity, but cannot be guaranteed 100%.

To complement the information provided by the optimal discriminant of minimal dimensions, the prediction models resulting from including all the sub-groups with two and three variables were obtained, and all those the models that provided an estimate of correct classification of 100% were selected (Table 3). The optimal classification model and the complementary models were used to establish the following classification criterion: (a) one of the categories of "frontal deformation" or "no frontal deformation" was assigned if the optimal classification model and at least seven of the eight complementary optimal classification models (all minus one) matched the allocation/prediction; and (b) if not, it was assigned to the doubtful category. The application of the classification functions to the sample of 50 men of the Selknam ethnic group provided the following results: 22 individuals were classified into the category of "frontal deformation" (44.0% ± 13.8%); 26 individuals were classified in the category "without frontal deformation" (52% ± 13.9%); and 2 individuals were classified as "doubtful" (4.0% ± 5.4%). By standardizing the variables, the application of the criterion to the 42 male individuals of the Yamana ethnic group provided the following classification: 11 individuals with frontal deformation; 15 without frontal deformation; and 16 classified as doubtful. Likewise, application of the criterion to the 16 individuals of the Alakaluf provided the following classification: 5 individuals with frontal deformation; 6 individuals without frontal deformation; and 5 doubtful individuals. The opposition of these results (40% of individuals with frontal deformation) with those obtained by visual inspection of the craniograms (frontal deformation is infrequent in the male individuals of both ethnic groups) showed reduced efficiency when the discriminant functions between ethnic groups were exchanged.

For women of the Yamana ethnic group, the variables with higher capacity for discriminating bregmatic deformation were (Table 2): BPL (basion–prosthion length), SSA (zygomaxillar angle), ZYB (bizygomatic breadth), NAA (prosthion–nasion–basion angle), PRA (nasion–prosthion–basion angle), FRS (frontal subtense: nasion–bregma subtense), FRA, BNL (basion–nasion length), MDH (mastoid

TABLE 3 Prediction models for men of the Selknam ethnic group (100% in correct classification estimate)

Model	Coefficients for logistic regression equations							
	Constant	FRA	FRS	LAR	VRR	PAA	FOL	NBA
FRS, LAR (optimum (3.2))	−753.65		−27.63	12.45				
FRS, LAR, VRR (complementary)	−571.98		−23.86	11.77	−1.59			
FRA, LAR, VRR (complementary)	−3232.06	19.16		14.46	−8.19			
FRS, LAR, PAA (complementary)	38.06		−16.89	7.72		−3.73		
FRA, LAR, PAA (complementary)	−1246.87	9.36		11.35		−9.38		
FRS, LAR, NBA (complementary)	95.76		−21.13	7.62				−6.35
FRA, LAR, NBA (complementary)	−8287.81	53.67		19.81				−17.09
FRS, FRA, LAR (complementary)	−166.36	−3.31	−29.16	11.55				
FRS, LAR, FOL (complementary)	−835.95		−26.44	12.63			0.93	

height), IML (malar length), OCF (lambda-subtense fraction), PRR (prosthion radius), ZMR (zygomaxillar radius), AVR (molar alveolus radius) and BRA (nasion–bregma–basion angle).

All the variables presented statistically significant differences between individuals with and without bregmatic deformation (*P*-value <.10) and, except for SSA, NAA, MDH, IML, OCF, and BRA, all the variables had a discriminant capacity over 20%. The variables that presented greater discriminant capacity were BPL, ZYB, FRA, and FRS. The BPL variable showed a high correlation with the variables NAA (ρ[BPL, NAA] = 0.69) and PRA (ρ[BPL, PRA] = −0.67), an intermediate correlation with ZYB (ρ[BPL, ZYB] = 0.54), FRA (ρ[BPL, FRA] = 0.48) and FRS (ρ[BPL, FRS] = −0.46) and a low correlation with the SSA variable (ρ[BPL, SSA] = 0.12). The ZYB variable presented an intermediate correlation with SSA (ρ[ZYB, SSA] = 0.46), FRA (ρ[ZYB, FRA] = 0.37) and FRS (ρ[ZYB, FRS] = −0.31) and a low correlation with the other variables (ρ < 0.2). The FRS and FRA variables showed a very high correlation between them (ρ[FRS, FRA] = −0.92) and an intermediate correlation with the previous variables. The PRA variable showed a high negative correlation with NAA (ρ[PRA, NAA] = −0.76), an intermediate correlation with FRA and FRS (ρ(PRA, FRA) = −0.38, ρ(PRA, FRS) = 0.37) and a low correlation with SSA (ρ[PRA, SSA] = 0.01). The SSA variable presented an intermediate correlation with FRA (ρ[SSA, FRA] = 0.42) and FRS (ρ[SSA, FRS] = 0.26) and a low negative correlation with NAA (ρ[SSA, NAA] = −0.07). Finally, the NAA variable showed an intermediate correlation with the variables FRS and FRA (ρ(NAA, FRS) = −0.32, ρ(NAA, FRA) = 0.30). The other observed variables (48) have a discriminant capacity under 20% and have not shown statistical significance when the Kruskal-Wallis test was applied (*P*-value >.10 without adjustment for multiplicity) or the measurement was not very reliable.

The logistic regression model provided the predictive equation PF (3.1), where

$$\eta = -6165.37 + 24.16 \cdot \mathrm{BPL} + 28.88 \cdot \mathrm{SSA} \qquad (3.3)$$

With the optimal classification model (3.3) and the complementary models (Table 4) the following classification criterion was established: (a) one of the categories, “bregmatic deformation” or “no bregmatic deformation” was assigned if the optimal classification model and at least two of the three complementary classification models (all minus one) matched in the allocation/prediction; and (b) if not, it was assigned to the doubtful category. The application of the classification functions to the sample of 32 women of the Yamana ethnic group provided the following results: 4 individuals were classified into the category “bregmatic deformation” (12.5% ± 11.5%); 25 individuals were classified into the category “without bregmatic deformation” (78.1% ± 14.3%); and 3 individuals were classified as “doubtful” (9.4% ± 10.1%). Application of the criterion to 21 female individuals of the Selknam ethnic group with prior standardization of the variables, provided the following classification: 16 individuals without bregmatic deformation and 5 classified as doubtful. Likewise, application of the criterion to 19 female individuals of the Alakaluf ethnic group provided the following classification: 1 individual with bregmatic deformation; 14 individuals without bregmatic deformation and 4 doubtful individuals. Contrast of these results

TABLE 4 Prediction models for women of the Yamana ethnic group (100% in correct classification estimate)

Model	Coefficients for logistic regression equations							
	Constant	BPL	SSA	ZYB	NAA	PRA	FRS	FRA
BPL, SSA (optimum (3.3))	−6165.37	24.16	28.88					
ZYB, NAA(complementary)	−2384.48			11.02	12.35			
PRA, FRS (complementary)	2699.84					−33.65	−19.66	
PRA, FRA (complementary)	−24.85					−27.31		13.78

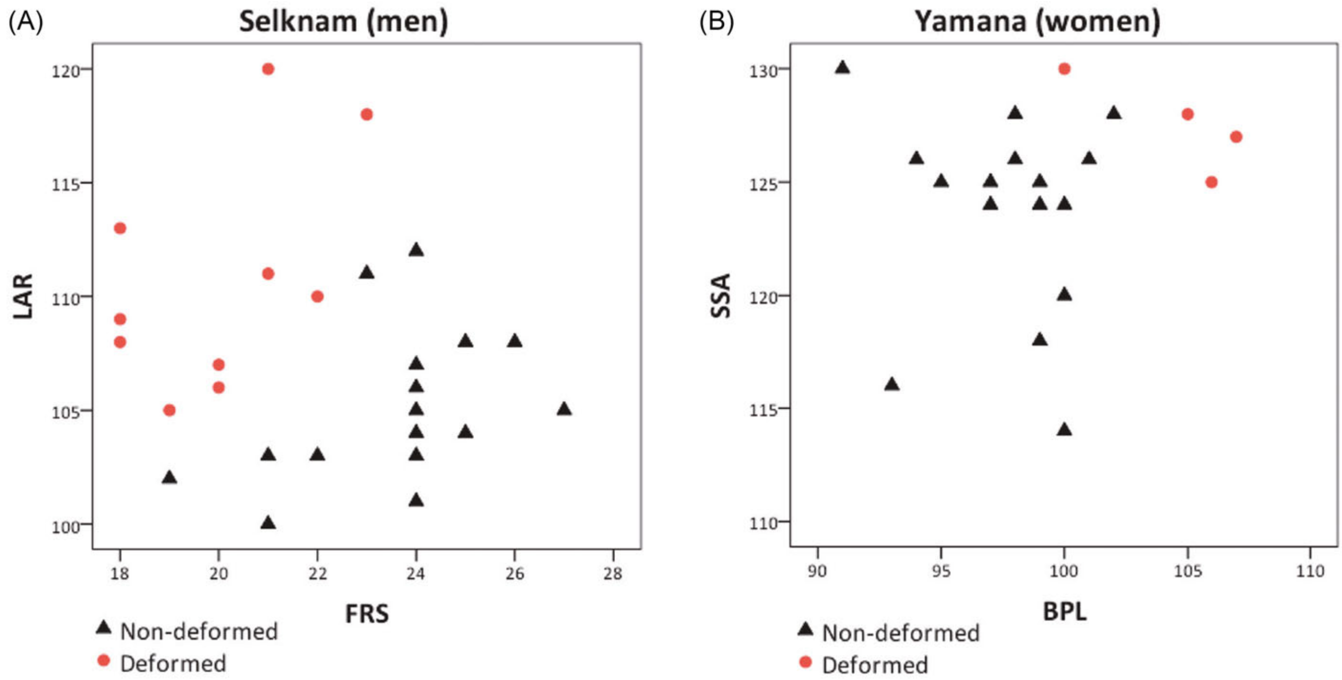

FIGURE 5 Two-dimensional representation of the deformed and non-deformed individuals in the most informative dimensions. (a) Selknam men and (b) Yamana women

does not concord with the visual observation carried out with the craniograms.

The geometrical representation of the men of the Selknam ethnic group in the dimensions that define the optimal discriminant (FRS and LAR) showed morphological continuity in men with and without frontal deformation (Figure 5a). Likewise, the representations in the most informative dimensions (BPL and SSA) also show morphological continuity in Yamana women, with and without bregmatic deformation (Figure 5b). Both groups are separated by a frontier (real or fictitious). A distribution with greater intensity in the core of the population (center) is not observed, neither is a progressive reduction of density observed when the individuals are further from the center. Furthermore, significant differences were observed in the distribution of the individuals into three categories (deformed, not deformed, and doubtful) when the homogeneity test between sexes was applied in the Selknam ethnic group ($\chi^2 = 9.18$; $P = .0102$). On the other hand, no significant differences were obtained in the Yamana ethnic group ($\chi^2 = 4.21$; $P = .1217$).

4 | DISCUSSION

In accordance with the classification established by Dembo and Imbelloni (1938), the frontal deformation observed in the men of the Selknam ethnic group is of a slanting circular type and is compatible with the use of flexible straps or leashes. The deformed crania present a flattened frontal area (the FRA is more open; and the subtense (FRS) is shorter), the parietal gains length (the Lambda radius (LAR) is longer; and the parietal angle (PAA) is sharper), the length of the foramen magnum (FOL) is lesser, the Basion-Nasion-Bregma angle (NBA) is sharper and finally the radius at the vertex (VRR) is greater. The significance of the differences in the observed variables is compatible with the results reported in other studies: Australia (Brown, 1981), Peru (Anton, 1989), north-central Peru (Pomeroy, Stock, Zakrzewski, & Lahr, 2010), south central Andes (Cocilovo et al., 2011), and Korea (Jung & Jin Woo, 2017). A similar deformation pattern, the morphological differences between ethnic groups or populations (Perez, 2007), and the differential interactions between the deformation of the cranial vault and the structures of the face and the base of the cranium (Anton, 1989; Cheverud, Kohn, & Konigsberg, 1992; Jung & Jin Woo, 2017; Kohn, Keigh, Jacob, & Cheverud, 1993; Rhode & Arriaza, 2006) explain why the classification functions are not interchangeable and why the sub-groups of more informative variables do not match overall.

On the other hand, the bregmatic deformation observed in the Yamana women is compatible with the application of a vertical compressive force (top-down) that displaces the cranial mass in the other two directions (antero-posterior and transversal; Kohn et al., 1993). In particular, the deformation observed was seen in three units or functional complexes: (a) forward projection of the face due to nasal and sub-nasal prognathism (BPL, AVR, PRR, PRA, BNL, NAA, and ZMR) and effects on the bone structures of the face (ZYB, SSA, and IML); (b) depression of the bregmatic area (more flattened frontal (FRA y FRS) along with higher bregma (BRA)); and (c) action of the muscles associated with the mastoid process and the occipital area (MDH and OCF). This type of variation in the vault has also been described in the literature: Peru (Anton, 1989), Peru and India (Cheverud et al., 1992), south central Andes (Cocilovo et al., 2011; Rhode & Arriaza, 2006), north-central Peru (Pomeroy et al., 2010), and Korea (Jung & Jin Woo, 2017).

The results obtained show that the frontal deformation in Selknam men affects almost half of the population (44.0% ± 13.8%). This estimate may present a positive bias (excess estimate), since the Selknam crania, available in museums and collections may have been acquired for being more spectacular/more deformed (Gusinde, 1989 [1937]; Turbon et al., 2017). Given that it is an extinct population, the possible bias in the sample is difficult to corroborate with objective evidence. The estimated percentage of individuals with frontal deformation and the morphological continuity in men with and without deformation is not very compatible with the following hypothesis: (a) hierarchy within the social organization or belonging to a social status (the percentage of individuals with frontal deformation should be lower and the morphological differentiation between deformed and nondeformed should be sharper); (b) identification of the ethnic group (the percentage of individuals with deformation should reach the entire population or almost all of it); and (c) identification of the individuals of the ethnic group that inhabit the territories with most resources and that have exclusive right of use (the morphological differentiation between deformed and nondeformed should be sharper). By contrast, the results obtained are compatible with the tying of babies in cradles or frames, with the use of leather visors (kóxen) to protect the babies from reflected sunlight or fires, with esthetic preferences of the mothers, and with the work of loading or dragging. The differential adjustment in tying babies into cradles, the differential intensity in the work and the differential esthetic preference of mothers may explain the morphological continuum (nonhomogeneity) and the percentile distribution of the individuals with deformation, doubtful and without deformation.

The opposite results between sexes bring in new elements that enable the compatibility of the previous hypotheses to be considered in greater depth. Without evident frontal deformation in Selknam women or with significantly lower deformation percentages than the ones observed in men, it becomes highly debatable to attribute the frontal deformation to the use of tying and/or transport systems for babies in cradles or frames and to the use of visors to protect babies. On the other hand, the specialization of activities by sex and the esthetic differentiation between them may explain the differential results observed in men and women. Using isolation and an assumed biological and cultural primitivism as a basis (Lubbock, 1904), the frontal deformation in Selknam men has been related to the retention of a number of ancestral genetic characteristics. The results obtained in frontal deformation, morphological continuity and pseudo-uniform distribution of individuals with and without deformation (44 vs 52) are compatible with patterns in which the variance is found within the population and not between populations. For this reason the retention of genetic characteristics (Lande, 1977; Relethford & Blangero, 1990; Von Cramon-Taubadel, 2014) is a somewhat implausible hypothesis for explaining frontal deformation. Even more so when bearing in mind that the frontal deformation has not been observed in Selknam women and is infrequent in individuals examined from the Yamana and Alakaluf. At the same time, the natural selection that responds to the stress caused by the extreme climatic conditions (temperature and humidity) has been related to patterns of variation of the face (nasal region), but not with the frontal region (Hubbe, Hanihara, & Harvati, 2009; Von Cramon-Taubadel, 2014).

Finally, the possibility of post-mortem deformation has not been considered given that this would involve an asymmetric deformation, which has not been observed in the crania studied (Jurda, Urbanova, & Kralik, 2015; Lyman, 1994). For all the above reasons, the activities of loading or dragging and esthetic deformation are the hypotheses that most closely match the results obtained. The frontal deformation observed in Selknam men is compatible with dragging firewood to keep fires burning, dragging vegetable material to reinforce the structure of the cabins, dragging domestic utensils when changing camp and dragging heavy pieces of meat from the hunt. These activities were described as everyday ones in populations of Tierra del Fuego (Gusinde, 1982 [1931]; Pique, 1999). On the other hand, the frontal deformation attributed to male Selknam is compatible with the results described in the literature for the southern zone of the American sub-continent (Del Papa, Aimé, & Bonilla, 2017; Guichón, 2002).

The results obtained in this study show that the bregmatic deformation in women of the Yamana ethnic group affects a part of the population (12.5% ± 11.5%) and that the spatial distribution in the BPL y SSA dimensions shows a morphological continuity in women with and without deformation (Figure 4a, b). Cocilovo et al. (2011) showed that intentional deformation of the neurocranium also affected the facial dimensions. Establishing if the affected facial variables in our study come from deformation of the neurocranium, or are the result of other physical activities, such as para-masticatory actions, are beyond the scope of this study and we cannot make any pronouncements in this regard.

The results are not very compatible with the following hypotheses: (a) identification of the ethnic group (the percentage of individuals with deformation should include the entire population); (b) use of systems to tie babies in cradles or frames (the frontal deformation would affect the frontal region and not the bregma); (c) use of leather visors (the deformation would affect the frontal region and not the bregma; and (d) post-mortem deformation (the crania would present asymmetries). With developed frontal lobes and little robustness of the crania in Yamana women, neither is it reasonable to relate the bregmatic deformation with the retention of a set of ancestral genetic characteristics. On the other hand, associating bregmatic deformation with social status is compatible with the percentage observed of individuals with deformation, but this hypothesis does not match the social organization of the Yamana. The economic work unit was the nuclear family (couple and offspring), the groups were made up of a few families, and the relationship between families was one of equality, respect, independence and coexistence when hunting parties were formed (Gusinde, 1986 [1937]). Finally, relating esthetic preferences of the mothers with bregmatic deformation is somewhat inconsistent, given that this type of deformation is hardly visible to peers.

For all the above reasons, workload is the hypothesis that most closely matches the results obtained. The bregmatic deformation is compatible with gathering vegetables and animals and, in particular, with loading and transporting baskets on the head and in leather bags or sacks with a strap/handle that rests on the head and rests on the back. The large concentration of deposits of shells all along the coast give proof to this activity (Orquera & Piana, 2009) and ethnographic information attributes carrying out the activity to Yamana women (Gusinde, 1986 [1937]). On the other hand, the bregmatic deformation attributed to female Yamana is compatible with the results described in the literature for the southern zone of the American sub-continent (Del Papa et al., 2017; Guichón, 2002).

The artificial deformation of the cranium in humans has habitually been related to socio-cultural stimuli. In this context, it would be interesting to establish the type of deformation observed, and identify the individuals that present the deformation. Simple observation has enabled individuals with severe deformation to be identified. When the deformation is less pronounced, the use of quantitative tools enables subjectivity in classifying doubtful individuals to be reduced. With samples of reduced size and many variables, we have considered the pre-selection of variables (Kruskal-Wallis test and Λ-Wilks), we have applied logistic regression to obtain the optimal classifiers and, to achieve greater robustness, we have defined a multi-criterion decision rule (the replacement of more informative variables with others that are correlated has provided the complementary classification criteria). Furthermore, the graphical representation in the most informative dimensions (the variables that define the optimal discriminator) enables the morphological continuity or the separation of the groups to be observed (deformed and not deformed).

The application of objective criteria to separate the individuals with artificial deformation is interesting for many areas: to identify the invariant measurements that enable sexual dimorphism to be characterized; to relate the cranial variation to the genetic variation (geometric morphometrics with quantitative evolutionary genetics); and to place the information provided by the archeological remains, etc. The schemata introduced and the complementary information obtained in the homogeneity test between sexes is useful for studying frontal and bregmatic deformation in Fueguians, and is interesting for other studies, when the size of the sample is reduced (habitual in the field concerning us here). Finally, the predictive model proved to be very reliable when it was applied to the ethnic group for which it was built, while application of the classification function from one ethnic group to another provided insufficiently reliable results. The inter-ethnic differences in measurements of the cranium explain that the variability increases when a mixture of ethnic groups is considered and therefore the predictive capacity decreases. In an attempt to achieve more general classification functions (applicable to several ethnic groups), the possibility of standardizing the measurements obtained in the three ethnic groups and of obtaining classification functions with the standardized measurements was tried out. Unfortunately, standardization (adjusting the means) has not provided successful results either. For this reason specific studies in each population are inevitable.

To maximize objectivity in classification, it would be desirable to have general criteria that can be applied to multiple ethnic groups. Unfortunately, the general criteria described in the literature (Clark et al., 2007; O'Brien & Stanley, 2013) have provided too many classification errors when they have been used in the Tierra de Fuego samples. To reduce the magnitude of such errors, the introduction of specific criteria that provide greater reliability when applied to the populations for which they were designed can be justified. The approach proposed in this study (selection of the most important variables and obtaining a multi-criteria decision rule) has provided very reliable results when applied to the male Selknam and female Yamana populations, and is also applicable to other studies when the sample size is small. Unfortunately, the standardization of variables has provided discriminant functions with insufficient reliability when they have been applied to populations for which they have not been designed. For this reason, specific studies in each population continue to be an unavoidable reality.

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AUTHOR CONTRIBUTIONS

DT designed the study and directed the implementation. AL and MS contributed to the design and analyzed the results.

All authors drafted the manuscript, edited the manuscript for intellectual content, interpreted the findings, provided critical comments and reviewed the submitted manuscript.

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