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DSP: A TOOL FOR PROBABILISTIC SEX DIAGNOSIS USING WORLDWIDE VARIABILITY IN HIP-BONE MEASUREMENTS

DSP : UN OUTIL DE DIAGNOSE SEXUELLE PROBABILISTE À PARTIR DES DONNÉES MÉTRIQUES DE L'OS COXAL

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ABSTRACT

Determination of the sex of human bone remains represents a crucial stage in any palaeoanthropological study. The palaeobiological or palaeoethnological interpretations depend on its reliability. It is acknowledged that the adult hip-bone (*os coxae*) is by far the best non-population-specific indicator for reliable sex determination of adults. However, we clarify here a certain number of limitations which lower the reliability and ease of application of the usual methods. We propose a new tool—Probabilistic Sex Diagnosis (DSP: Diagnose Sexuelle Probabiliste)—based on a worldwide hip-bone metrical database (2040 adult specimens of known sex from 12 different reference populations). Sex is determined by comparing the specimen's measurements to those from the database and by computing the individual probability of being female or male, from any combination of at least four variables among ten. This method is very easy to learn and apply; it provides sex diagnosis for any anatomically modern human, whatever population the specimen belongs to. Numerous combinations allow sex diagnosis of either well—preserved hip-bones or damaged ones. DSP is thus useful for both archaeological and forensic purposes. Its accuracy is close to 100%. The DSP computing program is available at the following web link: *http://www.pacea.u-bordeaux1.fr/publication/dspv1.html*

Keywords: probabilistic sex diagnosis (DSP), hip-bone, osteometrics, anatomically modern humans, worldwide variability, bioarchaeology, forensic anthropology.

RÉSUMÉ

La détermination du sexe à partir des restes osseux humains représente une étape cruciale de toute étude paléoanthropologique. De sa fiabilité dépend la pertinence des interprétations paléobiologiques ou palethnologiques. Il est admis que l'os coxal mature est le meilleur indicateur, non spécifique à une population, pour réaliser une diagnose sexuelle fiable. Cependant, nous explicitons ici un certain nombre de limites qui abaissent la fiabilité et la facilité d'application des méthodes usuelles. Nous proposons un nouvel outil de Diagnose Sexuelle Probabiliste (DSP) basé sur les données métriques de l'os coxal, à partir d'un échantillon intégrant la variabilité mondiale (2040 os coxaux adultes provenant de 12 échantillons de référence). Le sexe d'un spécimen est déterminé à partir de n'importe quelle combinaison d'au moins quatre variables parmi dix, en calculant la probabilité individuelle d'appartenir au groupe masculin ou féminin de la base de données. Cet outil est d'un emploi très simple et est applicable à tout Homme anatomiquement moderne, quelle que soit

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son origine. Les nombreuses combinaisons disponibles permettent de déterminer le sexe de la plupart des os coxaux, même mal préservés. Son application concerne tant la recherche archéologique que la médecine légale. La méthode se révèle très fiable, avec un taux de détermination correcte proche de 100 %. Le logiciel est téléchargeable à l'adresse : http://www.pacea.u-bordeaux1.fr/publication/dspv1.html

Mots-clés : *diagnose sexuelle probabiliste (DSP), os coxal, métrique, Hommes anatomiquement modernes, variabilité mondiale, paléobiologie, médecine légale.*

INTRODUCTION

Individual identification (age at death and sex estimation) is the first basic step in the study of skeletal biology or cultural traits of past populations. Most scholars agree that sex diagnosis of adult skeletons can be performed easily and with high reliability (for ex.: Mays, Cox 2000; Ubelaker 2000). However, the overall reliability depends on the method and on the skeletal data taken into account: from 80% for cranial traits (Masset 1986) to 95% for the hip-bone (Sjøvold 1988). It depends also on the population itself: "*Estimates of sex therefore can be difficult if the observer is not familiar with the overall pattern of variability within the population from which the sample is drawn the overall*" (Buikstra, Ubelaker 1994: 16). The hip-bone is the most suitable bone because of its marked sexual dimorphism which results mainly from selective constraints on males and females imposed by locomotion and childbearing. It is very probable that the current pattern of pelvic sexual dimorphism took place in early modern humans approximately 100-150 ky ago (Hager 1989; Rosenberg, Trevathan 2002; Marchal 2003). The sexual dimorphism of the hip- bone is non-specific for populations, which is not the case for other parts of the skeleton (Bruzek 1991; Buikstra, Ubelaker 1994; Bruzek *et al*. 2005). However, current methods using visual as well as morphometric traits of the hip-bone still appear to be problematic.

Visual methods, such as the one proposed by Ferembach *et al*. (1980), take into account various traits of the hip-bone, each being scored and weighted, and sex determination is made according to a final rating which separates males from females. This approach is known to be very subjective and to require an experienced observer, and is even more unreliable when the final score is close to the separating value. Great improvements have been made by Bruzek (2002), focusing on morpho-functional traits of the hip-bone (*i.e*. the sacro-pelvic, acetabular and ischio-pubic elements, representing sexual dimorphism as a whole) and minimizing subjectivity with the help of a simple rating (yes/no) and a detailed description of the traits. Three points remain negative: the method is still difficult to apply for the inexperienced; to be fully reliable, a complete hip-bone is necessary; and sex determination may not be possible if female and male traits are equally represented.

Discriminant functions (DF) using hip-bone measurements have an advantage over visual methods. Indeed, measurement is less subjective than rating, and learning such a method is much easier. At least four pelvic DFs have been proved to be reliable enough (95%) and are not population-specific, as they take into account the three morpho-functional parts of the hip bone (see Bruzek 1992; Murail *et al*. 1999). For each DF, sex determination depends on the computation of a discriminant score (DS) which is compared to the discriminant value (DV) separating males from females. The problem lies in the existence of an overlapping area between male and female distributions. Thus, the closer to DV is the DS, the less reliable is the diagnosis. For example, in case of DV = 0 ($F < 0 < M$), a DS of 10 points clearly to a male diagnosis, but if DS = 0.1, the risk of error would be very important. Furthermore, minor fluctuation of the DV does exist between populations, which increases the influence of the overlapping area (Rogers 2005 ; Bruzek *et al*. 2005). Another limitation is the necessity of complete preservation of the hip-bone, which is not always the case in archaeological contexts.

For all these reasons, we wished to avoid as much as possible the limitations described above (Houët *et al*. 1999). First of all, we disregarded visual traits and focused on hip-bone measurements, which eliminates the problem of long-time training and reduces the errors of inter-observation (Bruzek *et al*. 1994). Instead of dealing with a population-specific discriminant value, we propose to compute, for each specimen, the probability of its being male or female, which implies a statistical decision-making process when determining sex. To minimize the problem of bone preservation (Waldron 1987), our diagnosis of sex is based on any combination of at least four variables among the ten proposed. These variables cover all the parts of the hip-bone. In order to take into account the entire variability of sexual dimorphism among modern humans, we have built a database using a

very large reference sample of hip-bones from four continents (collections where the actual sex of each specimen is known). The general principle of sex determination is to compute each specimen's individual probability of being male or female, by comparing its measurements to the worldwide hip-bone database.

MATERIAL AND METHODS

The first objective was to validate the hypothesis that all the different populations of modern humans share a common pattern of sexual dimorphism in their hip bones. Thus we studied reference samples from four different geographical areas: Europe, Africa, North America and Asia, including one to three subgroups for each of them (*table I*). The total sample assembles 2,040 non-pathological hip-bones from individuals of known age and sex. We selected 17 hip-bone measurements, according to previous definitions (*table II*).

The methodological approach included several steps:

1—A search for a common sexual dimorphism pattern among modern human populations with the help of discriminant analyses (DA):

a- A search for an overall European model from the three European samples (London, Paris and Coimbra).

b- A test of the European model on two independent samples (Cleveland and Washington).

c- A search for a new model including European and North American samples.

d- A test of the previous multi-regional model on African, Asian and European (Vilnius) samples.

2—A selection of a set of variables, according to their discriminant power and their preservation rate.

3—The development of the DSP tool for probabilistic sex diagnosis from the pooled worldwide sample.

All statistical analyses have been computed by the Statistica® package program. For each sample, assumption of univariate normality was verified by the Shapiro-Wilk test. Equal variances and covariances have been also verified in each sample by F and Box's M tests. Numerous discriminant analyses (DA) were carried out in order to identify, for each step, the combinations of variables which best separate males from females. Step by step, discriminant analyses were used with F to enter and F to remove values fixed respectively at 0.01 (default value) and 1.17. The power of a DA is given by the Wilks' lambda (McLachlan 1992) which ranges from 0 (perfect discrimination) to 1 (no discrimination at all). The posterior probability is the probability, for each specimen, of belonging to one of the groups; it is calculated from the Mahalanobis' distance, *i.e.* the distance between a specimen and the centroid of the distribution of all the specimens in a multi-dimensional space made up of the variables taken into account in the DA (Mardia *et al.* 2000). The computation of posterior probabilities was

	Country	City	Collection	Group	Date	Females	Males	Total
Europe	France	Paris	Olivier	-	Early 20th	62	98	160
	England	London	Spitalfields	-	18th-19th	31	31	62
	Portugal	Coimbra	Tamagnini	-	19th-20th	130	102	232
	Lithuania	Vilnius	Garmus	-	20th	112	108	220
Africa	South Africa	Johannesburg	Dart	Zulu	Early 20th	153	153	306
				Soto	Early 20th	58	52	110
				Afrikaner	Early 20th	56	56	112
North-America	USA	Cleveland [Ohio]	Hamann-Todd	Black	Early 20th	57	56	113
				White	Early 20th	56	56	112
		Washington DC	Terry	Black	Early 20th	110	106	216
				White	Early 20th	102	97	199
Asia	Thailand	Chiang-Mai	Forensic	-	Late 20th	96	102	198
Total						1023	1017	2040

Table I—Reference samples used in this work.

Tabl. I - Échantillons de référence utilisés dans ce travail.

made with an equal prior probability for male and female groups.

For each step, data were scanned to look for aberrant data (extremely low or high values, erroneous keyboarding, etc.), using single variable analyses (Houët 2001) in male and female groups. Values were excluded when $p < 0.001$. For sex determination, a posterior probability equal or superior to 0.95 was considered to be our threshold. Performance of a DA was thus defined by two criteria: the percentage of specimens whose sex is determined (*i.e.* $p \geq 0.95$) and the accuracy rate (percentage of specimens correctly determined).

Variables	Brief definition	Reference
PUM (M14)	Acetabulo-symphyseal pubic length	Bräuer 1988
SPU	Cotylo-pubic width	Gaillard 1960
DCOX (M1)	Innominate or coxal length	Bräuer 1988
IIMT(M15.1)	Greater sciatic notch height	Bräuer 1988
ISMM	Ischium post-acetabular length	Schulter-Ellis *et al*. 1983
SCOX (M12)	Iliac or coxal breadth	Bräuer 1988
SS	Spino-sciatic length	Gaillard 1960
SA	Spino-auricular length	Gaillard 1960
SIS (M14.1)	Cotylo-sciatic breadth	Bräuer 1988
VEAC (M22)	Vertical acetabular diameter	Bräuer 1988
HOAC (M22)	Horizontal acetabular diameter	Bräuer 1988
PUBM	Pubic tubercle—acetabular length	Schulter-Ellis *et al*. 1983
ISM	Maximum ischium length	Thieme, Schull 1957
AB	Greater sciatic notch breadth (between points A and B)	Novotny 1975
AP	Length between points A and P	Murail *et al*. 1993
BP	Length between points B and P	Murail *et al*. 1993
AC	Posterior chord of the sciatic notch breadth	Novotny 1975

Table II—The 17 previously selected measurements. In bold, the ten variables selected for the probabilistic sex diagnosis tool ("M" refers to the codes of Martin's measurements in *Bräuer 1988).*

Tabl. II - Les 17 variables sélectionnées en amont de l'étude. En gras, les dix variables prises en compte dans le logiciel DSP (« M » se rapporte aux codes selon Martin in *Bräuer 1988).*

RESULTS

Starting with the European sample (pooled specimens from London, Paris and Coimbra), numerous combinations of measurements were tested, which revealed that the best ones occurred when the three morpho-functional parts of the hip-bone (sacro-iliac, acetabular and ischio-pubic sections) were simultaneously taken into account. At least four variables appeared to be necessary to describe the common sexual dimorphism among these three pooled samples. We selected eight variables, among which any combination of at least four variables could be used for sex determination. Distribution of posterior probabilities and accuracy are very successful (*fig. 1*). With the chosen 0.95 threshold, sex is determined for 95.9% of the sample, and the accuracy rate is 100% (*table III*). This demonstrates that there is a common pattern of sexual dimorphism for the three different samples.

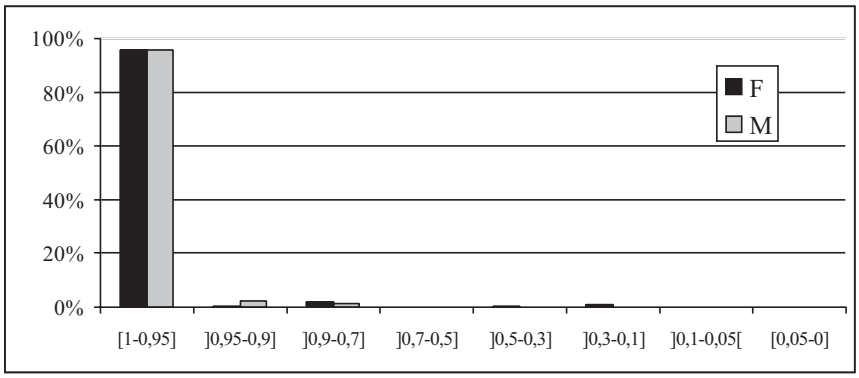

Fig. 1—Distribution of posterior probabilities in the European model (eight variables). Posterior probability is the probability of belonging to the real sex of each individual. At a 0.95 threshold, sex is determined for 95.9% of the sample and the accuracy is 100%.

Fig. 1 - Distribution des probabilités a posteriori *dans l'échantillon européen (huit variables). La probabilité* a posteriori *correspond à la probabilité pour un cas féminin d'appartenir au groupe féminin et réciproquement pour les cas masculins. Au seuil de 0,95, le sexe est déterminé pour 95,9 % de l'échantillon et la fiabilité est de 100 %.*

This first database was then used to assess specimens from North American samples (European and African origins). Results were consistent (*table III*): for example, the Afro-American sample (Terry and Hamman-Todd collections) was diagnosed in 92% of the cases, with an accuracy rate of 98.6%. This proves that hip-bone measurements express a common sexual dimorphism shared by different populations, even if samples are not included in the first reference database.

	8 variables			Best combination of 4 variables			"Worst" combination of 4 variables		
Samples	W.L.	Sexing%	Accuracy	W.L.	Sexing%	Accuracy	W.L.	Sexing%	Accuracy
European model: London, Paris, Coimbra	0.159	95.9%	100%	0.188	92.8%	100%	0.321	69.7%	98.3%
North American sample African origin		92%	98.6%		86.9%	98.6%		66.1%	98.6%
North American sample European origin		93%	100%		89.5%	99.6%		65%	97.4%

Table III—Test of the European model on the North American target sample. Variables in the model: ISMM, PUM, SPU, AB (best combination), HOAC, SCOX, DCOX, IIMT («worst» combination); W.L.: Wilk's lambda; sexing%: percentage of specimens whose sex is determined (p ≥ 0.95); accuracy rate: percentage of specimens correctly determined.

Tabl. III - Test du modèle européen sur les séries nord-américaines. Variables dans le modèle: ISMM, PUM, SPU, AB (meilleure combinaison), HOAC, SCOX, DCOX, IIMT (moins bonne combinaison) ; W.L. : lambda de Wilk ; sexing % : pourcentage d'individus sexés au seuil de 0,95 ; accuracy : fiabilité de la diagnose sexuelle.

The European and the North American samples were then pooled and the same analysis was carried out. Not surprisingly, a large majority of the previously selected variables were the same, and only two were different (HOAC, IIMT being changed to AC and ISM). The distribution of posterior probabilities in this model is very good, with 99.7% of determined specimens and an accuracy of 99.3% (*table IV*). It is quite logical that, compared to the previous analysis, the integration of the North American variability into the model has increased both the percentage of sexed specimens and the accuracy.

The evidence for the reliability of our method is provided by the sexing of other samples, according to this pooled European-North American matrix (*table IV*). Each sample, whatever its origin (African, Asian or Lithuanian), produces a high percentage of sexed specimens and more importantly, high accuracy (minimum 98.7%). Thus, the European-North American model is strong enough to describe the worldwide variability of the sexual dimorphism of the hip-bone and to allow a reliable sex diagnosis in other samples. We note that what we call the "worst" combination of four variables only refers to the decreasing percentage of sexed specimens, while the accuracy remains extremely high.

	8 variables			Best combination of 4 variables			"Worst" combination of 4 variables		
Samples	W.L.	Sexing%	Accuracy	W.L.	Sexing%	Accuracy	W.L.	Sexing%	Accuracy
European and North American model (all origins)	0.178	99.7%	99.3%	0.196	86.9%	99.7%	0.27	76%	99.6%
Thai sample		94.1%	100%		90.5%	100%		75.5%	100%
Zulu sample		88.7%	98.8%		84.6%	98.8%		66.2%	99%
Soto sample		86%	100%		84.4%	100%		63%	100%
Afrikaner sample		95.1%	100%		88.8%	100%		70.8%	100%
Lithuanian sample		94.4%	100%		91.7%	100%		71.6%	98.7%

Table IV—Test of the European and North American model on the African, Asian and Lithuanian samples. Variables in the model: ISMM, PUM, AC, SPU (best combination), AB, SCOX, DCOX, ISM ("worst" combination); W.L.: Wilk's lambda; sexing%: percentage of specimens whose sex is determined (p ≥ 0.95); accuracy rate: percentage of specimens correctly determined.

Tabl. IV - Test du modèle européen et nord-américain sur les individus d'origine africaine, asiatique et lituanienne. Variables prises en compte dans le modèle : ISMM, PUM, AC, SPU (meilleure combinaison), AB, SCOX, DCOX, ISM (moins bonne combinaison) ; W.L. : lambda de Wilk ; sexing % : pourcentage d'individus sexés au seuil de 0,95 ; accuracy : fiabilité de la diagnose sexuelle.

THE TOOL FOR PROBABILISTIC SEX DIAGNOSIS (DSP)

These results led us to propose a new tool for sex diagnosis. All the previous samples were pooled into a single large reference database. After analyses, the variables isolated from this overall model are the same as in the European-North American model, which is evidence that the extent of the entire variability of the dimorphism of the hip-bone has been reached. However, for practical use, two measurements which are sensitive to inter-observer error and quite difficult to acquire properly (AB and AC) have been replaced by two other measurements (SA and SS). To improve the percentage of sexing in poorly preserved archaeological contexts, we also added two other variables (SIS et VEAC) which appear to have a good preservation rate. These two variables should be resorted to only if it is not possible to get a minimum of four variables from the previous eight measurements.

Finally, we propose a set of ten variables (*table II*) and the possibility to compute the probability of being male or female for any combination of at least four variables among those ten (848 combinations depending on the state of preservation of the hip-bone). Table V sums up the results from this overall model. The accuracy rate is very high in any case, ranging from 98.7% to 99.63%. Depending on the number of variables taken into account, the percentage of sexed specimens varies from 40.23% to 90.76%.

The DSP tool uses a simple spreadsheet program (Excel® sheet)[4] where one must record the maximum of data required for each specimen (measurements in mm); then the probability for each specimen of being male or female is automatically computed, with an equal prior probability for male and female groups. It works with a minimum of four variables but one must be aware that the more variables there are, the likelier it is that a significant probability will be obtained. Variables are sorted from left to right in decreasing order of discriminant interest. Sex should be determined only if the posterior probability is greater or equal to the 0.95 threshold, which means a risk of error of 0.05 which is the maximum required for reliable palaeobiological studies (Bruzek 1996; Scheuer 2002).

Table VI gives four examples of sex diagnosis. Specimens A and B are determined (respectively female and male), while C is not ($p < 0.95$). Specimen D illustrates another possibility of DSP: only three measurements are available but a fourth one (PUM) can be estimated through a minimal and a maximal value. In both cases, posterior probabilities indicate the same sex determination (female) which will be the final diagnosis with a probability of at least 0.98.

In addition, the data acquired are compared through an automatic analysis to the range of the overall database, in order to avoid any erroneous measurement or keyboarding (if out of range, a red color invites the user to check his/her data). The DSP computing program also presents a detailed description of all the measurements needed, with helpful pictures.

Combinations	% sexing	Accuracy rate
10 variables (see *table I*)	90.71%	99.63%
8 variables (without SIS and VEAC)	90.76%	99.63%
Best combination of 4 (DCOX, PUM, SPU, IIMT)	86.69%	99.61%
“worst” combination of 4 (SIS, VEAC, SA, SS)	40.23%	98.75%

Table V—Results of the combinations from the worldwide model. Sexing%: percentage of specimens whose sex is determined ($p \geq 0.95$); accuracy rate: percentage of specimens correctly determined.

Tabl. V - Résultats des différentes combinaisons du modèle mondial. Sexing % : pourcentage d’individus sexés au seuil de 0,95 ; accuracy rate : fiabilité de la diagnose sexuelle.

4. This tool for probabilistic sex diagnosis is available from the authors or downloadable at the following web link: http://www.pacea.u-bordeaux1.fr/publication/dspv1.html

Spec.	PUM	SPU	DCOX	IIMT	ISMM	SCOX	SS	SA	SIS	VEAC	P(F)	P(M)	Sex
A		26	192		96	142	64	80	34	47	0.996	0.004	F
B		28	212	38	112						0.020	0.980	M
C		27	204	42.5	108		73.5	74.5			0.308	0.692	ND
D(1)	**73**	25	194			150					0.999	0.001	F
D(2)	**69**	25	194			150					0.984	0.016	F

Table VI—Four examples of sex diagnosis with the DSP tool. P(F): probability of being female, P(M): probability of being male. Sex: sex determination using P(M) or P(F) ≥ 0.95. ND: not determined. In bold: measurements are PUM estimations for specimen D.

Tabl. VI - Quatre exemples de diagnose sexuelle avec le logiciel DSP. P(F) : probabilité d'être une femme ; P(M) : probabilité d'être un homme. Le sexe est déterminé si P(M) ou P(F) est supérieur ou égale à 0,95 ; ND : sexe non déterminé. Les mesures en gras sont deux estimations de la dimension PUM pour le spécimen D.

DISCUSSION AND CONCLUSION

These results clearly demonstrate that the adult hip-bone presents a common sexual dimorphism for all modern human populations. Furthermore, we observe that metrical data can express this pattern through a statistical process. The principle of sex determination, using both posterior probabilities and a threshold of 0.95, is highly reliable, more than any other method. The limited number of variables needed, the many workable combinations and the possibility of recording estimates (maximal and minimal data) also enable sex determination of a high number of specimens from archaeological sites, even when poorly preserved. For those individuals which remain undetermined, there exists one more possibility through secondary sex diagnosis, which takes into account specific non-pelvic sexual dimorphism within the archaeological sample (see Murail *et al*. 1999). We also believe that DSP can be of great help in forensic cases. Forensic methods often include a preliminary step to determine the population to which the specimen belongs (*i.e*. "race 'or' ancestry" attribution for forensic scholars), before using population-specific standards. The advantage of DSP is that it is non-population-specific and thus usable without any previous or prejudged attribution to a particular population; furthermore, it provides a real probability for determining sex that is particularly useful for forensic purposes.

What about the misclassified specimens? Indeed, the error rate is very low, from 0.39% to 1.25%, depending on which model is chosen as a reference. There is no statistical difference of misclassification between males and females. Misclassification could be explained by individual variation in the sex differentiation of hip-bones. Generally speaking, errors could and do also exist among the reference collections. For example, specimen no.28 from Coimbra (not included in the database) is said to be a 41 year-old male, but is obviously female in its morphological traits and DSP. DNA analysis eventually proved that the specimen was indeed a female and that there had been an erroneous attribution in the reference catalogue (Fily *et al*. 1999).

We have shown that our database takes into account the entire variability of the sexual dimorphism of the hip-bone, even if we were not able to find any reference collections from Oceanic, Arctic or South American populations. However, our results are consistent with the distribution of a common sexual dimorphism, even among populations as strongly differentiated as those of European, South African and Asiatic origin. If we accept the hypothesis that the hip-bone in all anatomically modern humans is mainly adapted to both locomotion and parturition, DSP is applicable for all specimens of our species. For example, we applied it to Upper Paleolithic specimens and did not observe any contradiction, whatever combination of measurements was used (Henry-Gambier *et al*. 2002, in press).

On the contrary, using DSP for humans which are not anatomically modern is far less reliable. Neanderthals, for example, have been shown to present major differences in pelvic morphology compared to modern humans (Rak, Arensburg 1987; Rosenberg 1988; Marchal 2000). When applying DSP to the Kebara 2 specimen (one relatively well-preserved Neanderthal pelvis), the sex determinations obtained were opposite, depending on the combinations used (especially if pubic length is included

or not). No such contradictory results have been observed for our database, which underlines the specificity of the Neanderthal hip-bone conformation. We thus strongly recommend that DSP be used only for anatomically modern humans.

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