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Weibull analysis characterizes the breaking properties of dry-cured ham slices

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ABSTRACT

The breaking strength (σ) and stress–strain relation of several muscles [*biceps femoris* (BF), *semitendinosus* (ST) and *semimembranosus* (SM)] and the subcutaneous fat (SF) from a Spanish dry cured ham (Protected Designation of Origin of white ham from "*Teruel*") have been analysed by the uniaxial tensile test in order to predict the mechanical behaviour of this meat product. Thirty pieces were analysed and the stress–strain curves were obtained. A great dispersion of the σ values was observed. This leads to the necessity of employing statistical analyses to illustrate the extent to which strength values may vary. The Weibull analysis was applied to estimate the fracture probability. SM and SF showed the highest characteristic strength. The low values of the Weibull modulus indicate that dry-cured ham tissues behave as brittle materials. The stress–strain curves present characteristic forms for BF, ST and SM, which may be associated with their composition and the extent to which they are affected by the curing process.

1. Introduction

Textural characteristics of food are important aspects for consumer acceptance. The rheological behaviour of food can be evaluated using large strain methodologies (compression, torsion, tension or shear), which may be performed empirically or fundamentally (Bourne, 2002; Foegeding, Brown, Drake, & Daubert, 2003; Kilcast, 2004). Currently, the most commonly used instrumental method is Warner–Bratzler (shear test) and Texture Profile Analysis, TPA (compression test). The compression parameters obtained with TPA have been employed by many authors in their evaluations of meat products (Bruna, Fernández, Hierro, Ordóñez, & de la Hoz, 2000; Houben & van't Hooft, 2005; Hoz, D'Arrigo, Cambero, & Ordóñez, 2004; Visessanguan, Soottawat, Riebroy, & Thepkasikul, 2004).

Among the essential methods that can be used to study the rheological behaviour, the tensile test is the best suited for structural investigations (Purslow, 1985). The test can be carried out on raw or cooked meat. The performance of this test allows obtaining a load deformation curve (stress–strain curve) to complete rupture, in which the fracture strength corresponds to the maximum force supported by the material. Other parameters from the load deformation curve can be measured, including breaking strength, total energy to fracture, modulus of elasticity and breaking strain (Bourne, 2002; Honikel, 1998).

The tensile test has been used to monitor the mechanical properties of myofibres during *rigor mortis* onset and after rigor (Lepetit & Culioli, 1994; Willems & Purslow, 1996), to study the changes of mechanical tension properties of single meat fibres during *post-mortem* storage (Christensen, Young, Lawson, Larsen, & Purslow, 2003), and to determine the effect of cooking temperature on whole meat, single muscle fibres and perimysial connective tissue (Christensen, Purslow, & Larsen, 2000; Lepetit & Culioli, 1994; Lewis & Purslow, 1989; Mutungi, Purslow, & Warkup, 1995, 1996; Willems & Purslow, 1996). However, there is little information about tensile measurements on other meat products, namely dry cured ham, in spite of their repercussions and importance for the appropriate handling (e.g. the assessment of their behaviour in the slicing and packing processes) of this products.

The data obtained by tensile test could offer valuable complementary information about dry cured ham behaviour against both slicing operation and vacuum packaged. When these packages are opened and the ham slices are taken out, many of them break because the product breaking strength is less than the superficial adhesion force between the product surfaces. To solve this problem it would be useful to know if a meat product is suitable to be sliced and vacuum packed, i.e., slices with a breaking strength greater than the resistance offered by the adhered portions.

Usually the rheological and mechanical properties of the meat products are given as mean values with their corresponding deviation or standard error. However, several statistical tools may be used to model experimental data and to obtain more accurate information

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about these properties, especially to determine the mechanical properties of a non-isotropic meat product, including the breaking strength. One of these statistical analyses is the Weibull distribution, which is usually used for the determination of static and dynamic mechanical properties of several materials (Borrero-López, Hoffman, Bendavid, & Matin, 2009; Weibull, 1959). Weibull's analysis of fracture is based on a weakest link hypothesis, in which the strength of a body involves the products of survival probabilities of the individual volume elements, so that failure of the whole body will take place as soon as the material strength is surpassed at one element containing the critical flaw (Borrero-López et al., 2009).

Spain is a traditional manufacturer of cured meat products and the ham is the most emblematic product with the highest commercial value. It makes a significant contribution to the Spanish economy. The dry cured ham is a non-homogeneous product that undergoes a salting process and then is subjected to a long dehydration/ripening period (usually more than 1 year) during which the dynamics of the migration of the water and salts is balanced (NaCl, nitrate and nitrite) (Arnau, Guerrero, Casademont, & Gou, 1995) and the characteristic flavour is developed. An important part of the production comes under Protected Designation of Origin (PDO) of Spanish white ham, "*Jamón de Teruel*" (European Commission, 2006; MAPA, 1993), which is produced at the Northeast of Spain from white pigs fed with commercial feeding and a minimum of 9 months of air-curing. This PDO has had the highest sales over the past few years, with sales of more than a million units in 2009 corresponding to approximately 45% of the annual production in relation to the other PDOs in Spain (MARM, 2009).

The aim of this work was to apply uniaxial tensile tests to dry-cured hams to illustrate the extent to which the breaking strength may vary and to obtain the stress–strain curves in order to provide a complete characterization of the mechanical behaviour of this meat product. With this aim, samples from the *biceps femoris* (BF), *semitendinosus* (ST) (both as model of internal muscle) and *semimembranosus* (SM) (as an external-type) *Mm* and the subcutaneous fat (SF) were taken. In the present paper, the Weibull distribution was employed to model the breaking probability of the abovementioned tissues of a traditional Spanish dry-cured ham, but could also be used in other meat products and other features with similar high variability.

2. Materials and methods

2.1. Description of the samples

Thirty Spanish dry-cured hams from three different commercial brands were purchased in retail shops. All dry-hams were elaborated following the procedure of "Protected Designation of Origin (PDO) Teruel".

The dry-cured hams analysed in this study corresponded to the left leg of the hogs with a final weight of about 8.5 kg and they were cured for 12 months of cured. Samples from muscles and tissues abovementioned were taken from each dry-ham. The samples were stored at 5 ºC until analysis.

2.2. Physico-chemical analysis

Dry matter (DM), pH, water activity (a_w) and salt content were determined in triplicate samples. For analyses, portions of about 200 g were finely cut. DM was determined by drying the sample at 110 ºC to constant weight and the results were expressed as a percentage (AOAC, 2006). The pH was determined in a distilled water homogenate (1:9) (w/v) of the sample (10 g) using a Crison Digit-2001 pH meter (Crison Instruments LTD, Barcelona, Spain). Minced samples were employed to determine a_w using a Decagon CX1 hygrometer (Decagon Devices Inc., Pullman, WA, USA) at 25 ºC. The salt content (chlorine as sodium chloride) was determined by AOAC method 935.47 (AOAC, 1995).

2.3. Tensile test

Uniaxial tensile tests were performed using a TA.XT2i SMS Stable Micro Systems Texture Analyser (Stable Microsystems Ltd., Surrey, England) with the Texture Exponent Programmes. The test was carried out at about 22 ºC. A minimum of three rectangular pieces (about 9.0 × 3.0 cm and 0.2 cm thickness) of each tissue were taken per ham using an electric slicer meat cutter machine (mod. SP 300 CE DOM, Beckers, Italia) to obtain the correct thickness and a thin-bladed sharp knife (to adjust rectangular piece dimensions). To standardize sampling and in accordance with previous works (Herrero et al., 2007; Herrero et al., 2008; Honikel, 1998), these pieces were cut in a dumb-bell shape, approximately 4.0 × 1.0 cm in the narrowest zone and 0.2 cm thickness per sample. To obtain the dumb-bell shape from a continuous cut and a smoothly contoured surface, one sheet-metal cutting mould, of the same shape and the same dimensions and with sharpened cutting edges, was manufactured. To minimize damage, samples were separated from the cutting moulds using a scalpel when adhesions occurred. To determine the mechanical behaviour of the muscle fibres, the samples were cut parallel to the fibre direction. The subcutaneous fat samples (surrounding the *biceps femoris* muscle) were cut parallel to the muscle surface. After cutting, the width and thickness in the centre of the samples were checked with a calliper (Digit Cal, Tesa, Brown and Sharpe, Swiss). The above dimensions were considered to calculate the original cross-sectional area of the test-piece.

For uniaxial tensile analysis a load cell of 5 kg was employed. Each sample was gripped between two tensile grips (A/MTG). Initial grip separation was 2.5 cm and the samples were subjected to extension at a strain rate of 1.0 mm/s until rupture (Herrero et al., 2007). The curves of stress and strain were obtained using the recorded data by Texture Exponent Programmes (Stable Microsystems Ltd., Surrey, England) and the Origin 8.0 programme. The cross-sectional area (thickness × width) of the sample was considered to calculate the stress (N cm^{-2}). Breaking strength or ultimate tensile strength, corresponded to the maximum stress that samples can withstand while being stretched before breaking (stress at fracture) and it was taken as the highest point of the stress–strain curve (Herrero et al., 2007, 2008). To calculate the breaking strength, only results for those test-samples which

Table 1
Dry matter (DM, % wet matter), NaCl content (% DM), water activity (a_w) and pH of different muscles and subcutaneous fat from dry-cured ham.

Tissue	pH	a_w	Dry matter	NaCl
Biceps femoris muscle	6.08 a (5.96, 6.22)	0.91 a (0.90, 0.92)	45.70 c (42.19, 49.20)	10.49 a (9.55, 11.73)
Semimembranosus muscle	6.46 a (6.02, 6.60)	0.91 a (0.89, 0.92)	57.67 b (55.13, 60.21)	7.12 b (7.02, 8.40)
Semitendinosus muscle	5.94 a (5.87, 6.10)	0.90 a (0.88, 0.92)	50.60 c (48.60, 52.59)	6.31 b (5.43, 7.27)
Subcutaneous fat	6.23 a (6.07, 6.39)	0.82 b (0.80, 0.85)	88.27 a (83.85, 92.69)	0.56 c (0.39, 0.73)

Data are the mean values and 95% confidence intervals. a, b, c: different letters in thesame column indicate significant differences ($p < 0.05$).