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Impact of Combining Tumbling and Sous-Vide Cooking Processes on the Tenderness, Cooking Losses and Colour of Bovine Meat

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Abstract: This study investigated the effect of combining tumbling and sous-vide cooking processes on the tenderness, cooking losses and colour of bovine *Semitendinosus* (ST) muscles sampled from Charolais-breed cows. Half of the ST muscles were tumbled for 12 h with a compression rate of 40%. All muscle samples, whether tumbled or not, were then sous-vide cooked at 50 °C, 60 °C or 80 °C for 1 h or 4 h. After cooking, we measured the shear forces (SF), cooking losses, total water content and the main colour characteristics of pre-tumbled and non-tumbled meat pieces. Pre-tumbled meat pieces had 20% lower SF values than non-tumbled meat pieces, regardless of the cooking conditions applied. All meat pieces cooked at 50 °C had significantly higher ($p < 0.05$) SF values and lower ($p < 0.05$) cooking losses than meat pieces cooked at 60 °C or 80 °C. Pre-tumbled meat pieces showed significantly lower cooking losses ($p < 0.001$) than non-tumbled meat pieces. Applying the tumbling process before cooking led to an increase in meat colour lightness values ($p < 0.001$), and the colour parameters were significantly affected ($p < 0.05$) by temperature, cooking time, and temperature × cooking time interaction. Combining a 12-h tumbling process with cooking at 60 °C appears to provide the best compromise between increasing meat tenderness and limiting cooking losses.

Keywords: beef tenderness; shear force; lightness; vacuum cooking; tumbling

1. Introduction

Meat tenderness is a major determinant of consumer satisfaction and a major factor influencing the likelihood of repeat purchases and willingness to pay premium prices for meat and meat products [1]. Tenderness depends on a cluster of ante-mortem and post-mortem factors, including mainly production practices (notably breeding, feeding, housing, transport, stunning, and exsanguination), ageing after slaughtering and cooking procedures. Tenderness also differs among meat muscles in the same carcass depending on anatomical location and composition (e.g., fibre type) of the muscle [2–4]. In an effort to provide high-quality products and meet consumer demand, the meat industry has developed a number of techniques for improving meat tenderness through chemical (e.g., brining, marinating), enzymatic (e.g., adding of plant proteases or/and microbial-based enzymes) and/or mechanical processes (e.g., blade tenderization, high pressure or ultrasound processing, tumbling) [5,6].

Tumbling is a processing technology used in the meat industry for the manufacture of raw and/or cooked hams and marinated or seasoned products. Tumbling is usually performed in baffled rotating drums [7,8]. During the process, mechanical energy is transmitted to the free-falling meat as they strike against the baffles, which promotes

mechanical deformation of the meat tissue [7]. The resulting cellular disruption and muscle structure damage promote the diffusion of brine into the meat tissue [9,10], break down the meat surface, and enhance the extraction and solubilization of muscle proteins [11–15]. The modifications that the meat tissue undergoes during tumbling enhance global cooking yield [16–18] by increasing both the water-holding capacity [14,19,20] and the tenderness and juiciness of the tumbled pieces of meat [19,21]. Tumbling is therefore a mechanical meat tenderization process, just like blade tenderization. Tumbling is now well accepted and widespread in the meat industry [6], mainly due to the economic advantages of increasing the water content and thus weight of the products and due to its performance in spreading and intensifying the penetration of marinades and seasonings [22].

Sous-vide cooking is a technique for cooking raw materials by vacuum packing them in heat-stable plastic pouches and then heating them in a water bath at relatively low temperatures for times far longer than usual cooking times [23]. Sous-vide cooking processes usually use cooking temperatures below 100 °C for cooking times that range from several hours to more than one day. This heat treatment became popular in the catering industries in the 1970s [23–28]. For red meat, sous-vide cooking is typically performed at temperatures less than or approximately equal to 60 °C, in a process called low-temperature long-time (LTLT) cooking [29]. Sous-vide cooking lends food superior sensory and technological characteristics and improves the retention of important nutrients for human health, such as vitamins, minerals and antioxidants [30–32]. Compared to other cooking methods, sous-vide cooking promotes efficient and uniform heat transfer inside the meat and helps ensure product safety by limiting the risks of microbial contamination [33]. All these aspects make sous-vide cooking a widely-used cooking technique that has steadily gained popularity in restaurants, centralized kitchens, and catering operations [27,29,34].

Various studies have reported that the tenderness, juiciness and colour of sous-vide cooked meat vary as a function of the temperatures and cooking times used [4,27,35–40]. The tenderness and sensory acceptability of cooked meat are conditioned by the intensity of the heat treatment that affects the texture and water-holding capacity of the meat and the denaturation of meat proteins. Sous-vide cooking meat at lower temperatures for a long time results in products with better sensory qualities and consistent tenderness and juiciness [41–44]. Indeed, myofibrillar proteins denature at around 50 °C, collagen fibre gels at temperatures close to 60 °C, and connective tissue becomes soluble as the temperature reaches 70 °C–80 °C [45,46]. The heating procedures, i.e., temperatures and cooking times, affect the quality of sous-vide cooked meat by promoting protein denaturation and water retention while simultaneously weakening the connective tissue and solubilizing the collagen [37,38,41,43,44,47].

N'Gatta et al. [15] recently reported that mechanical tenderization realized with a laboratory tumbling simulator significantly decreased the toughness of the muscle fibres and connective tissues of raw beef meat cuts and thus improved raw meat tenderness, provided that the tumbling process was carried out for at least 12 h. Here, with the aim of verifying whether the tumbling-induced improvement in tenderness observed on raw meat was not lost after cooking, this study investigated the combined impact of tumbling without marinating and *sous-vide* cooking on the tenderness, juiciness and colour of bovine *Semitendinosus* (ST) muscles. We would like to point out that we decided to use sous-vide cooking, first and foremost because it is a cooking method that allows a piece of meat to be cooked evenly at a set temperature (i.e., without a temperature gradient, unlike cooking on a grill, in a pan or in an oven), provided you wait long enough. In this way, it was possible to unambiguously link what is observed on the meat sample to the cooking temperature.

2. Materials and Methods

2.1. Raw Meat Materials

Eighteen ST muscles taken from both sides of nine Charolais cows slaughtered at age 52 ± 6 months were purchased locally from a butcher sourcing from a slaughterhouse that vacuum-packs bovine muscles 24 h after the animal is slaughtered. However, we

have taken care to ensure that all the muscles used came from animals raised by the same producer to limit the effect of variability related to rearing conditions. All muscles were, therefore, vacuum packed in polyamide/polyethylene (PA 20/PE 70) plastic pouches (SAS Boulegon Parry, Clermont-Ferrand, France) using a Multivac C200 vacuum packing machine (MULTIVAC Sepp Haggenmüller SE & Co. KG, Wolfertschwenden, Germany). The pouches had an oxygen permeability of less than 65 $g/m^2/24$ h and a water transmission rate of less than 5 $g/m^2/24$ h. The sous-vide packed pouches were stored at 4 °C until 21 days after the date of the slaughter of the animal, before being frozen at −20 °C until their final use. Before each experiment, the muscles were thawed in a cold room at 4 °C for 72 h. We then checked that the pH of each muscle was between 5.4 and 5.6.

We chose the ST muscle for two main reasons: first, it is a rather tough beef muscle, rich in collagen, and therefore suitable for tenderization by tumbling; second, its elongated and rather cylindrical shape allowed us to easily obtain, after trimming, a cylindrical piece of meat 18-cm long and 6.5-cm in diameter, weighing approximately 700 g. The muscles were trimmed in this way for technical reasons related to the laboratory device used for tumbling, which is described in N'Gatta et al. [15] and was developed by Daudin et al. [7]. The maximum length of the piece of meat to be tumbled had to be slightly shorter than the length of the compression piston (i.e., 18 cm vs. 20 cm) so that the whole piece of meat would be fully compressed. The diameter of the meat piece (i.e., 6.5 cm) was conditioned by the fact that, whatever the compression rate applied (40% in this study), the movement of the compression piston could not exceed 4 cm in any case, once in contact with the surface of the meat sample.

One of the two ST muscles taken from the same animal was mechanically tenderized using the laboratory tumbling simulator. The tumbling program used was 9500 consecutive compression cycles with 4.5 s per cycle, i.e., approximately 12 h, and a compression rate of 40%. During the tumbling tests, which were carried out in a cold room at 4 °C, the rotation speed of the meat samples was set at seven rotations per minute. The second ST muscle, which was not mechanically tenderized, was also stored at 4 °C for 12 h and then served as a control to investigate the effect of combining the tumbling and sous-vide cooking processes on the evolution of the meat tenderness, juiciness and colour.

2.2. Sous-Vide Cooking and Sampling of the Muscles

As mentioned in the previous section, the eighteen ST muscles were divided into two batches of nine muscles, which were either tumbled or not tumbled (the latter being used as a control), ensuring that the two muscles from the same animal were not in the same batch. Each batch of nine muscles was then divided into three batches of three muscles, with each new batch to be cooked at one of three set temperatures, either 50 °C, 60 °C or 80 °C (Figure 1). Before cooking, each muscle was cut into six 3-cm-thick slices that were randomly divided into two groups of three slices; these two groups of slices were cooked at the same temperature but at two different times: either 1 h or 4 h (Figure 1). To make cooking easier, each meat slice was vacuum packed in transparent PE plastic pouches (SAS Boulegon Parry, Clermont-Ferrand, France) and then cooked in a water bath (Memmert Type WNB29, Memmert GmbH + Co. KG, Schwabach, Germany) pre-heated at one of the three set temperatures (50 °C, 60 °C or 80 °C) for one of the two set cooking durations (1 h or 4 h). In order to achieve uniform heating of the meat slices and to prevent them from floating on the surface of the water bath, the slices were hung vertically from a stand placed above the water bath, which kept the slices completely immersed in the water bath and thus uniformly heated (Figure 1). The temperatures at the core of the meat slices were not recorded to avoid any loss of vacuum and leakage of liquid during the cooking process. We relied on the numerically predicted temperatures (Figure 2a). At this stage, we also ensured that the two ST muscles of the same animal, the one tumbled and the control, were cooked at the same temperature.
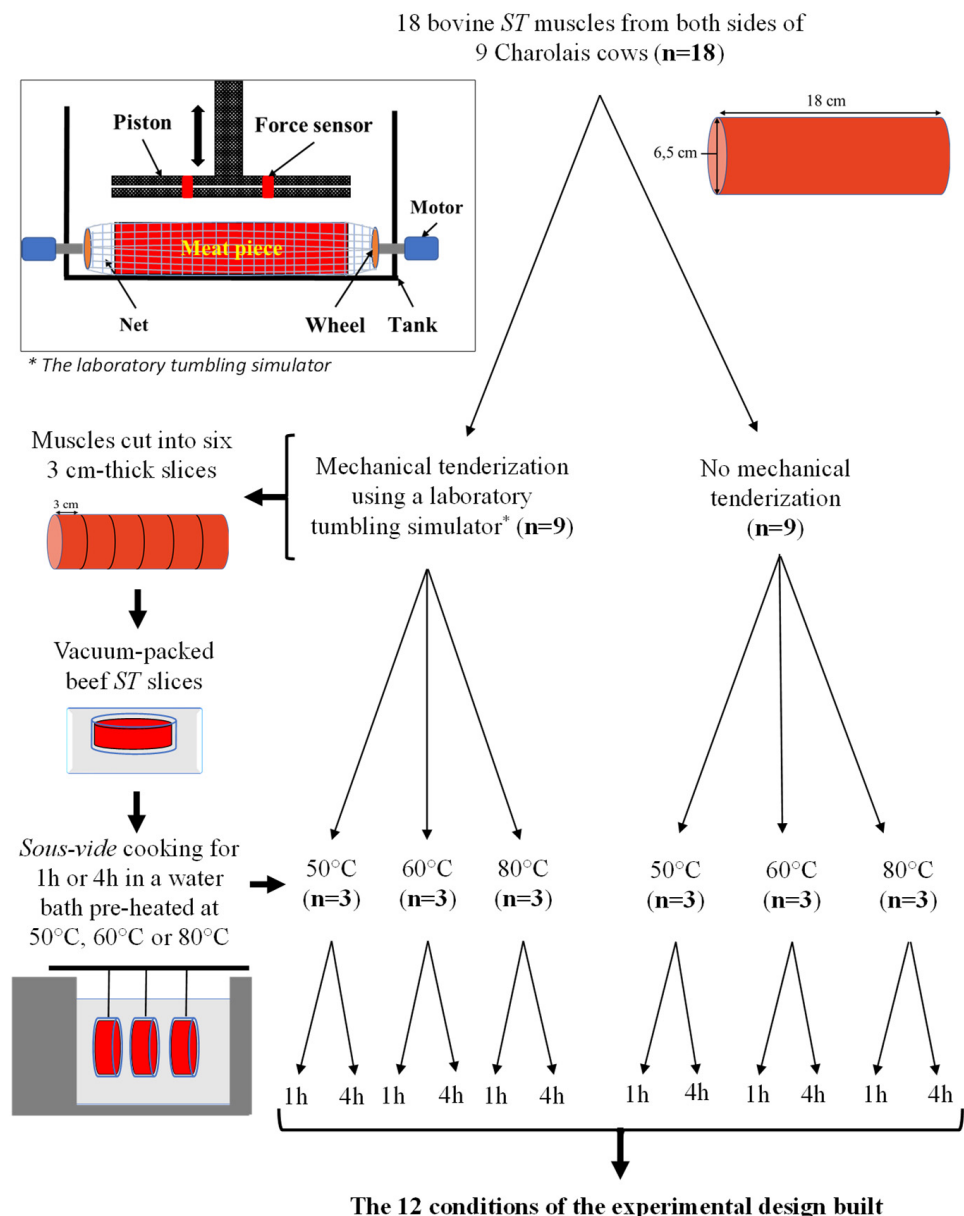
Figure 1. Schematic description of the experimental design built in this study.

In the end, the procedure implemented corresponded to a full factorial design with three factors, namely the cooking temperature with three levels (50 °C, 60 °C and 80 °C), the cooking time with two levels (1 h and 4 h) and the mechanical treatment with two levels (applied or not). In summary, each of the twelve conditions of this full experimental design was finally associated with nine 3 cm thick slices of ST muscles from three different animals (Figure 1).

The two cooking times (1 h and 4 h) were determined as sufficient for temperature homogeneity or stable water content in the sample, respectively. This was assessed through preliminary heat and mass transfer numerical simulations. Heat transfer was estimated using the model described by Supaphon et al. [28], which represents meat as a homogeneous solid in which heat transfer occurs by conduction and whose materials properties depend on the meat's constituent proteins, fat and water. This meat solid was wrapped in a thin layer representing the plastic pouch. Finally, surface flux on the plastic pouch was based on the values for an unstirred water bath reported by Kondjoyan et al. [48]. Mass transfer was estimated using the water loss model described by Kondjoyan et al. [48]. Heat and mass

transfers were solved for our meat sample geometry using COMSOL Multiphysics® 5.5 software (Comsol France, Grenoble, France). Therefore, regardless of the set temperature, a 1 h duration corresponded to the time required for the temperature in the centre of the meat slice to reach the temperature of the water bath (Figure 2a), and a 4 h duration corresponding to the time required for the meat slice to reach the equilibrium water content value (Figure 2b).
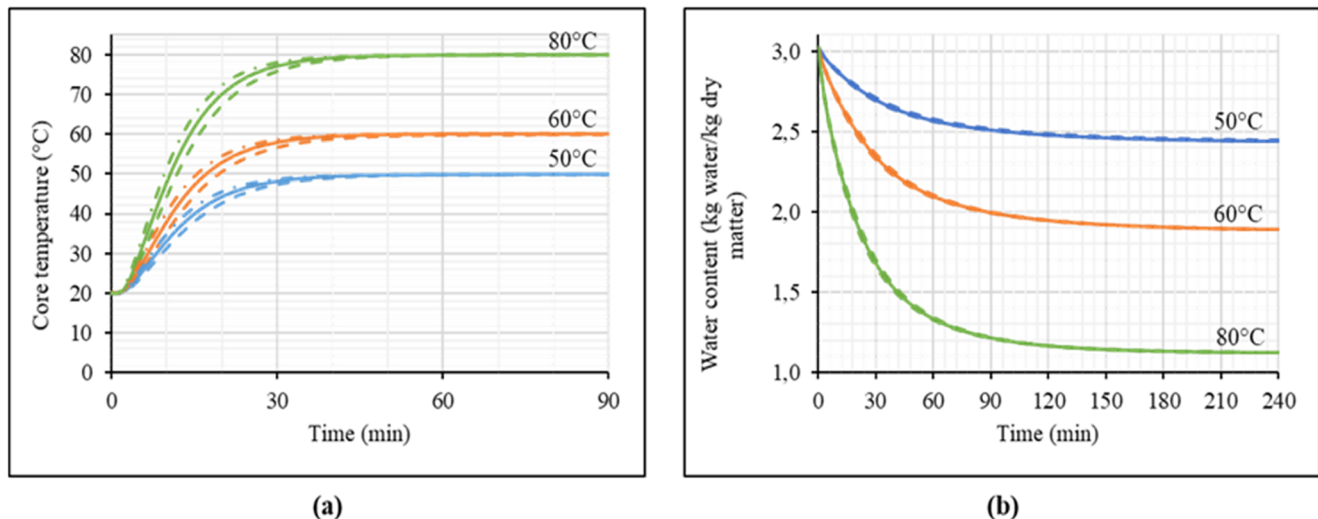

(a)   (b)

Figure 2. Simulation of (**a**) core temperature kinetics with heat conduction using Fourier's law, the material properties reported in [28], and piecewise linear interpolation to our temperatures of 'non-stirred water bath' heat transfer coefficients taken from Kondjoyan et al. [48], and (**b**) time-course of average water content based on the mass transfer relation and its parameters taken from Kondjoyan et al. [48] for a sous-vide-packed, 3 cm thick, 6.5 cm diameter slice of meat immersed in a water bath at temperatures of 50 °C (blue), 60 °C (orange) and 80 °C (green). Dashed lines are the upper and lower bounds of the estimation based on the propagation of uncertainties from the material properties and the boundary heat transfer coefficient.

2.3. Shear Force Measurement

Meat tenderness can be assessed by means of mechanical tests and thus instrumental measurements, such as, e.g., shear forces (SF). SF values were measured on the meat using a rectangular shear cell developed by Salé [49] and attached to a universal testing machine (Instron 5543, Instron S.A., Guyancourt, France). Prior to texture analysis, each slice of cooked meat was cut into ten $1 \times 1 \times 3 \text{ cm}^3$ blocks, taking every effort to keep the same orientation of the muscle fibres perpendicular to the shear blade. Each of the small meat blocks was sheared once at a crosshead speed of 50 mm/min, and then measured. The tenderness value of the meat corresponded to the mean value of the peak shear forces calculated from 30 tests (10 blocks per slice × 3 replicates) for each time–temperature combination, and was expressed in Newtons (N).

2.4. Cooking Loss

Immediately after cooking, each meat slice was immersed in iced water for 10 min to stop the cooking action of residual heat on the meat constituents. Once cooled, the meat pieces were then removed from the cooking pouches, gently wiped with a paper towel, and then weighed (PM34DR model, Mettler-Toledo, Viroflay, France). The difference in weight before and after heat treatment was used to calculate the cooking loss (CL), expressed as a percentage of the pre-cooking weight.

2.5. Total Water Content

The total water content (TWC) was evaluated according to the method described by Oillic et al. [50] on small meat samples, weighing 3 to 5 g. These samples were placed in a pre-heated oven (ED240 model, BINDER GmbH, Tuttlingen, Germany) and held at 105°C for 48 h. The weight difference of the meat samples before ($m_{-drying}$) and after ($m_{+drying}$) this drying period was used to determine the TWC value, expressed as a percentage of the pre-oven-drying weight: (TWC = 100 $\times (m_{-drying} - m_{+drying})/m_{-drying}$).

2.6. Colour Measurement

The colour of the cooked meat samples was assessed based on instrumental colour using a Konica Minolta CM-2500d spectrophotometer calibrated with a white plate (Konica Minolta Sensing Europe B.V., Bremen, Germany), with a D65 illuminator, an angle of 10° and a diameter of 8 mm. As sous-vide cooking in a water bath gave the meat surface a 'boiled' appearance, we decided to measure the colour of the meat slices 2 mm below this surface by removing a 2 mm thick layer from the surface of each cooked meat slice. After a blooming period of 1 min at room temperature, colour measurements were collected three times at different locations on each meat sample before calculating the mean value. Measurements were expressed as L* (lightness), a* (redness), and b* (yellowness) in the CIELAB system, as per AMSA methodology [51]. The redness and yellowness variables were used to determine chroma ($C^* = \sqrt{a^{*2} + b^{*2}}$) and hue angle ($H^* = \tan^{-1}(b^*/a^*)$).

2.7. Statistical Analysis

Data analysis was performed by using Statistica 13.0. Software (Statistica, TIBCO Software Inc., Palo Alto, Santa Clara, CA, USA). A three-way analysis of variance (ANOVA) was performed for each parameter measured (i.e., SF whose mean value, for each condition tested, was calculated from 90 individual samples prepared from three different ST muscles; CL whose each mean value was calculated from nine 3 cm thick slices prepared from three different ST muscles; TWC whose each mean value was calculated from 18 individual samples prepared from three different ST muscles; and L*, a*, b*, C*and H* whose each mean values were calculated from nine individual measurements performed on three different ST muscles) to determine the effects of mechanical treatment, temperature, and cooking time on these parameters. Tukey's HSD multiple comparison test was used to determine levels of statistically significant differences (*p*-value < 0.05) among mean values.

3. Results

3.1. Shear Forces

The average shear force (SF) values measured on the cooked meat pieces corresponding to the different mechanical and heating treatments are presented in Figure 3. Tumbling the 21 days aged meat pieces resulted in a significant decrease in SF values for all cooking procedures applied, thus confirming the tumbling-process-induced improvement in the tenderness of raw beef shown in N'Gatta et al. [15] persists even after cooking. SF values of the meat pieces decreased with increasing cooking temperature in both pre-tumbled and control meat pieces. Cooking meat pieces at 50 °C led to higher SF values compared to those cooked at 60 °C and 80 °C, which had significantly lower SF values (Figure 3). Increasing cooking time from 1 h to 4 h at 50 °C significantly increased (*p* < 0.05) the SF values of non-tumbled meat pieces (from 105 N to 121 N) but not those of pre-tumbled meat pieces (88 N vs. 92 N); (*p* > 0.05; Figure 3). Conversely, as shown in Figure 3, increasing cooking time at 60 °C and 80 °C led to a significant (*p* < 0.05) reduction in SF values for both control and tumbled meat pieces. The lowest SF values (about 40–45 N) were obtained in the case of 12 h tumbled meat cooked for 4 h at temperatures of either 60 °C or 80 °C. These values are globally twice as low as the values measured for tumbled beef meat cooked for 4 h at 50 °C (Figure 3).
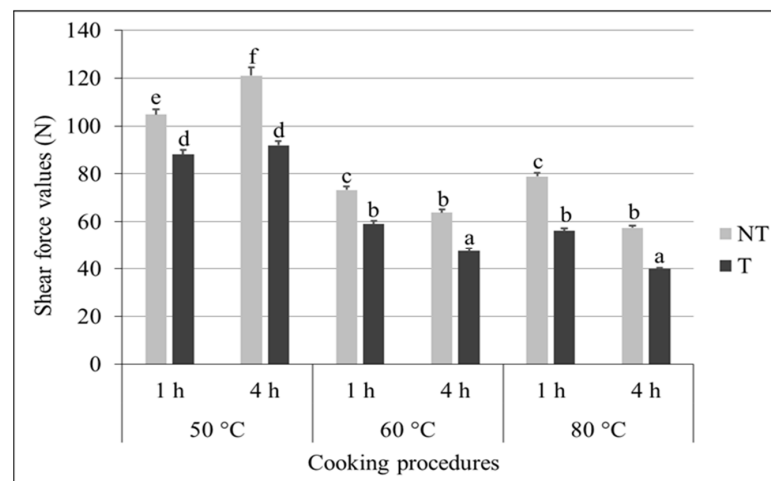
Figure 3. Shear force (SF) values measured on bovine *Semitendinosus* muscle samples previously tumbled (T) or not (NT, used as control) and then sous-vide cooked at 50 °C, 60 °C or 80 °C for 1 h or 4 h. The data correspond to mean values ± standard error (SE) calculated from 90 individual samples prepared from three different ST muscles. Different letters (a–f) refer to significant differences between all treatments.

The three-way ANOVA confirmed that all factors, i.e., mechanical treatment, temperature and cooking time, had significant effects ($p < 0.001$) on SF values (Table 1). Furthermore, the interaction between temperature and cooking time had a very significant effect ($p < 0.001$) and the interaction between mechanical treatment and cooking temperature had a significant effect ($p < 0.05$) on SF values, whereas the interaction between mechanical treatment and cooking time had no statistically significant effect ($p > 0.05$) (Table 1).

Table 1. Statistical analysis of the simple effects of the factors (tumbling process (Treat), cooking temperature (Temp), and cooking time (Time)) and their cross-effects (Treat × Temp, Treat × Time, and Temp × Time) on values of shear forces (SF), cooking losses (CL), total water content (TWC), lightness (L*), redness (a*), yellowness (b*), chroma (C*), and hue angle (H*) evaluated on sous-vide cooked bovine *Semitendinosus* muscle samples. NS = not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Variables	Treat	Temp	Time	Treat × Temp	Treat × Time	Temp × Time
SF	***	***	***	*	NS	***
CL	***	***	***	***	NS	***
TWC	***	***	***	NS	NS	NS
L*	***	***	***	***	NS	**
a*	NS	***	*	NS	NS	***
b*	NS	***	***	NS	NS	***
C*	NS	***	***	NS	NS	***
H*	***	***	***	NS	***	***

3.2. Cooking Losses

Cooking losses (CL) were significantly ($p < 0.05$) lower from tumbled meat pieces than control ones, regardless of heat treatment applied. Increasing temperature and cooking time led to an increase in CL values in both tumbled and control meat pieces (Figure 4). CL values ranged between 5–20% at 50 °C, 17–30% at 60 °C, and 35–44% at 80 °C. The difference in CL between pre-tumbled and non-tumbled (control) meat pieces decreased with increasing cooking temperature. In control meat pieces, the difference in CL values when the cooking time was increased from 1 h to 4 h was 7%, 7%, and 4% at 50 °C, 60 °C, and 80 °C, respectively (Figure 4). The lowest CL values were obtained for 12 h tumbled meat cooked for 1 h at 50 °C, which contrasts strongly with the result obtained for SF values.
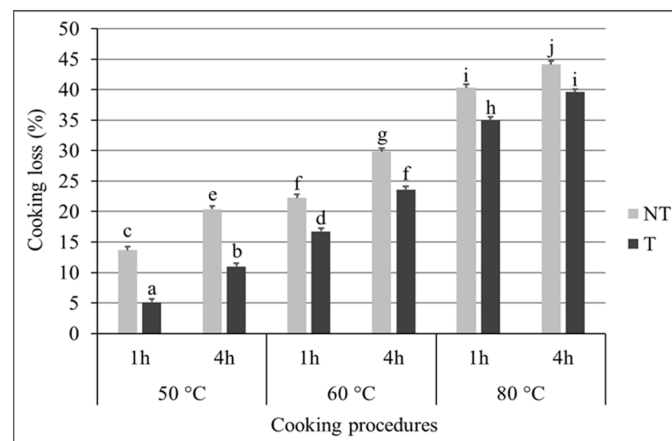
Figure 4. Cooking losses (CL) measured on bovine *Semitendinosus* muscle samples previously tumbled (T) or not (NT, used as control) and then sous-vide cooked at 50 °C, 60 °C or 80 °C for 1 h or 4 h. The data correspond to mean values ± standard error (SE) calculated from nine 3 cm thick slices prepared from three different ST muscles. Different letters (a–j) refer to significant differences between all treatments.

The three-way ANOVA revealed that, in addition to the direct effect of each of the three factors studied independently, the interactions of mechanical treatment × cooking temperature and cooking temperature × cooking time had very significant effects on CL ($p < 0.001$), whereas no significant effect was found for mechanical treatment × cooking time (Table 1).

3.3. Total Water Content

Total water content (TWC) values were slightly higher for pre-tumbled meat pieces than for controls, except for meat samples cooked for 4 h at 80 °C where the difference was no longer statistically significant (Figure 5). Increasing temperature and cooking time led to a decrease in TWC values for tumbled and control meat pieces, from slightly higher than 70% at 50 °C to slightly lower than 60% at 80 °C (Figure 5). This decrease in TWC with increasing cooking temperature is largely explained by the concomitant increases in CL (see above, Figure 4).

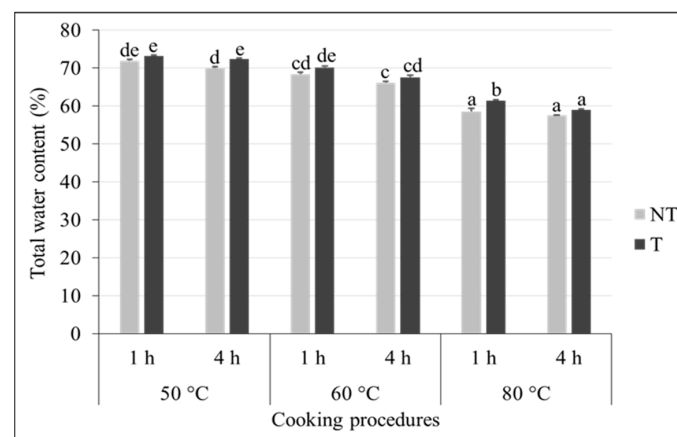**Figure 5.** Total water content (TWC) values measured on bovine *Semitendinosus* muscle samples previously tumbled (T) or not (NT, used as control) and then sous-vide cooked at 50 °C, 60 °C or 80 °C for 1 h or 4 h. The data correspond to mean values ± standard error (SE) calculated from 18 individual samples prepared from three different ST muscles. Different letters (a–e) refer to significant differences between all treatments.

Like SF and CL values, the three-way ANOVA showed significant effects ($p < 0.001$) on TWC of all factors, i.e., mechanical treatment, temperature, and cooking time, but no significant effects ($p > 0.05$) of any of the mechanical treatment × cooking time or temperature interactions (Table 1).

3.4. Meat Colour

The characteristic values of the colour of the tumbled and control meat pieces are reported in Table 2. The tumbled meat pieces presented higher lightness values (L*) than control meat pieces, especially after cooking at either 50 °C or 60 °C for 4 h (Table 2). Globally, increasing temperature and cooking time increased L* and decreased redness (a*), yellowness (b*) and chroma (C*) values. Hue angle values (H*) increased with increasing cooking temperature. Tumbled meat pieces had higher H* values than control meat pieces when cooking time was prolonged to 4 h (Table 2). Increasing cooking time decreased control meat H* values at 50 °C and 80 °C and tumbled meat H* values at 80 °C and increased the H* values in the other three configurations, i.e., at 60 °C in tumbled and control meat pieces and at 50 °C in tumbled meat pieces (Table 2).

Table 2. Lightness (L*), redness (a*), yellowness (b*), chroma (C*) and hue (H*) values measured on bovine *Semitendinosus* muscle samples previously tumbled (T) or not (NT, used as control) and then sous-vide cooked at 50 °C, 60 °C or 80 °C for 1 h or 4 h. The data correspond to mean values calculated from 9 individual measurements performed on three different ST muscles. Different superscript letters (a–e) refer to the significant differences between all treatment procedures, and the subscript letters x and y, when indicated, refer to significant differences between control (NT) and tumbled (T) muscle samples.

Temperature	50 °C		60 °C		80 °C		SE
Time	1 h	4 h	1 h	4 h	1 h	4 h	
			L*				
NT	51.37 [a] [x]	55.01 [b] [x]	57.93 [c]	59.71 [c] [x]	60.13 [c]	58.48 [c]	0.54
T	54.54 [a] [y]	59.14 [b] [y]	60.65 [bc]	63.16 [c] [y]	60.31 [bc]	60.15 [bc]	0.52
			a*				
NT	11.82 [cd]	12.02 [d]	10.08 [c]	7.60 [b]	2.36 [a]	5.77 [b]	0.60
T	13.07 [d]	11.04 [c]	10.09 [c]	6.84 [b]	2.69 [a]	4.06 [a]	0.65
			b*				
NT	22.38 [c]	19.05 [b]	21.91 [c]	17.24 [ab]	18.19 [ab]	16.16 [a]	0.46
T	22.85 [d]	21.28 [c]	21.83 [cd]	19.06 [b]	16.08 [a]	17.12 [a]	0.44
			C*				
NT	25.33 [e]	22.54 [cd]	24.13 [de]	18.84 [ab]	18.35 [ab]	17.20 [a]	0.58
T	26.33 [e]	23.97 [de]	24.06 [de]	20.25 [bc]	16.30 [a]	17.59 [ab]	0.64
			H*				
NT	62.22 [b]	57.73 [a]	65.38 [b]	66.17 [bc]	82.60 [d]	69.84 [c]	1.37
T	60.26 [a]	62.61 [ab]	65.32 [b]	70.26 [c]	80.51 [e]	76.67 [de]	1.26

SE: standard error.

The three-way ANOVA analysis showed that mechanical treatment had significant effects on meat L* and H* values ($p < 0.001$) while temperature and cooking time had significant effects on all colour parameters ($p < 0.05$; Table 1). The temperature × cooking time interaction had a significant effect on all measured colour parameters ($p < 0.01$ for L* and $p < 0.001$ for all others). The mechanical treatment × cooking time interaction only had a significant effect on H* values ($p < 0.001$) whereas the mechanical treatment × cooking temperature interaction only had a significant effect on L* values ($p < 0.001$; Table 1).

4. Discussion

4.1. Effect of Tumbling, Temperature, and Cooking Time on Shear Forces

This study found that the tumbling process combined with low-temperature and long-time sous-vide cooking of ST muscles previously aged for 21 days promoted tender meat pieces, as evaluated by measuring SF values. The effect of tumbling on reducing the SF values of meat pieces has been well documented for pork meat [10,19,21,52] but not for beef. Pietrasik and Shand [17] showed that extending tumbling time (to 16 h) decreased SF and hardness values by 50–60% in cooked beef roast samples previously injected with brine at 20% or 40% of their initial mass. Very recently, N'Gatta et al. [15] showed that the tumbling-induced decrease in the toughness of raw beef meat pieces evaluated through compression tests was due to a combined reduction in strength of both muscle fibre and connective tissue, i.e., to the degradation and breakdown of the muscle.

Here, we found that a higher cooking temperature led to lower SF values of control and tumbled meat pieces. Increasing cooking time from 1 h to 4 h led to a decrease in SF values of the meat samples cooked at 60 °C and 80 °C, whereas extending the cooking process at 50 °C led to a further increase in SF values in both the control and tumbled meat pieces. These results showing that increasing the cooking temperature tends to decrease SF values in beef are fully coherent with results from many previous studies, as discussed below. Indeed, by studying the effect of low-temperature long-time cooking on the toughness of bovine ST muscles, Christensen et al. [37] showed that SF values decreased when the cooking temperature increased from 53 °C to 63 °C. In the case of sous-vide cooked beef ST muscles, Vaudagna et al. [26] and Botinestean et al. [36] highlighted decreases in SF values when increasing cooking temperatures from 50 °C to 65°C and from 60 °C to 70 °C, respectively. Lepetit et al. [47] showed that the maximum stress values of meat pieces of Semimembranosus and Longissimus dorsi muscles extracted from cull cows decreased at cooking temperatures between 55°C and 60 °C. More recently, Naqvi et al. [4] reported that increasing cooking time while increasing temperature from 55°C to 75°C increased the reduction of the Warner Bratzler shear forces (WBSF) in ST and biceps femoris (BF) muscles from cows. Christensen et al. [37] studied the effect of heating temperature and time on beef meat toughness and showed that WBPF values of bovine ST muscles decreased significantly when the meat pieces were cooked at 58°C for 2.5 h and 7.5 h as well as at 55°C for 19.5 h. Roldán et al. [39] reported that sous-vide cooking lamb loins at 60 °C, 70 °C and 80 °C combined with a 24 h cooking time reduced the SF and hardness values. Most of the changes in meat toughness observed during cooking result from the effect of heat treatment on the meat's protein components, in particular the myofibrillar and connective tissue proteins. Christensen et al. [47] studied the effect of cooking temperature on the mechanical properties of whole meat, single muscle fibres and perimysial connective tissue and found that aggregate meat toughness increased in two separate phases, i.e., cooking at 40–50 °C, and again at 60–80 °C, but decreased during cooking at 50–60 °C. They attributed this decrease in meat toughness to lower resistance to breakage of the perimysial connective tissue due to partial denaturation and shrinkage of the collagen fibres.

The effect of heat treatment on meat texture is therefore a denaturation and solubilization of the muscle protein components, including sarcoplasmic, myofibrillar (in particular, myosin and actin) and connective tissue proteins. Tornberg [46] studied structural changes of meat proteins at different temperatures and showed that the aggregation of most sarcoplasmic proteins occurred between 40 °C–60 °C and that some of these sarcoplasmic proteins coagulated at temperatures up to 90 °C. Purslow et al. [45] showed that connective tissue, especially collagen, denatured at temperatures between 53°C and 63°C, and that collagen gelled between 60 °C and 70 °C. The denaturation and solubilization of connective tissue proteins tenderize the meat, whereas the denaturation of myofibrillar proteins toughens the meat [29]. These two opposite phenomena are more pronounced at extended cooking times [4,27,37], which could explain why SF values increased when the control meat pieces were cooked for 4 h at 50 °C but decreased at 60 °C and 80 °C.

4.2. Effect of Tumbling, Temperature, and Cooking Time on Cooking Loss and Total Water Content

Tenderness and juiciness are the two most important sensory attributes that influence consumer satisfaction with cooked meat [4,29]. CL and TWC values are key determinants of meat juiciness, as they influence the moisture content of the meat. Our results showed that CL and TWC values were very significantly influenced by the tumbling process, cooking temperature, and cooking time. Increasing cooking temperature and time increased CL values (Figure 4), and so TWC values consequently decreased (Figure 5). Tumbled meat pieces showed less CL than control meat pieces. This tumbling process-induced difference in CL values tends to get smaller with increasing cooking temperature, from about 10% at 50 °C to 5% at 80 °C. All these results agree with several previous studies [4,16,17,21,26,53]. Note, however, that the tumbling process itself, when carried out without marinating or brining, results in a weight loss of the meat pieces. Here, we assessed this initial weight loss due to tumbling as 5%–7% of the initial mass of the raw meat pieces. This weight loss before applying the cooking process could therefore greatly explain the difference in CL values observed when comparing the CL from tumbled versus non-tumbled meat pieces before and after cooking.

Lachowicz et al. [21] showed that increasing tumbling time decreased CL losses but differently according to the type of ham muscles: in *Biceps femoris* muscle, the decrease only became significant after 10 h of effective tumbling, whereas in *Quadriceps femoris* and *Semimembranosus* muscles, the lowest CL values were obtained after 6–8 h of tumbling. Pietrasik and Shand [17] showed that extending tumbling time to 16 h significantly decreased the percentage of water loss from meat. These results were due to the improvement of the water-holding capacity when increasing tumbling time, especially when tumbling is coupled with brining [17]. Moreover, they showed that moisture increased with increasing tumbling time in the case of beef roasts previously injected with brine at 20% or 40% of their initial weight, which results in a significant increase in post-cooking yield, particularly for the beef roasts injected with 20% brine [17]. On goat hams, Dzudie and Okubanjo [16] demonstrated that increasing tumbling time again increased moisture and reduced CL values. Similar results were found by Li et al. [54] who observed that longer tumbling times (up to 6 h) reduced CL values for pork hams after a 20% injection of brine. They also found that increasing cooking temperatures from 76°C to 96°C increased the CL values. Li et al. [54] explained that the higher CL values after short tumbling times (2 h) were due to muscle fibre disruption, whereas the lower CL values after extended tumbling times (4 h and 6 h) likely result from the increase in protein solubilization and pH value.

Here, CL values of tumbled and control meat pieces increased simultaneously with increasing temperature and cooking time (Figure 4). These results are in accordance with a number of previous studies [4,27,37,39,53,55]. CL values in meat are largely influenced by the structural changes in myofibrillar proteins that occur during cooking. Indeed, most of the water present in meat is located in the immediate vicinity of myofibrillar proteins. So, increasing cooking temperature causes denaturation and shrinkage of myofibrillar proteins in the 40 °C–90 °C range, while collagen shrinks at cooking temperatures around 60 °C [46]. The CL values observed for temperatures below 60 °C were therefore related to the transverse shrinkage of the muscle fibres that increased the space between the muscle fibres, whereas, above 60 °C, the cooking losses resulted from longitudinal shrinkage of the muscle fibres [39,53]. Supaphon et al. [28] recently studied CL and structural changes in Thai beef SM muscles cooked under vacuum and observed that the difference in CL values between 2 h and 6 h of cooking was reduced when the cooking temperature was increased from 60 °C to 80 °C. Furthermore, in the case of sufficiently long heat treatment times, Oillic et al. [50] showed that CL from different sizes of cubes and parallelepipeds cut from beef SM muscles were no longer dependent on the size of the sample but only on heating temperature.

4.3. Effect of Tumbling, Temperature, and Cooking Time on Meat Colour Characteristics

All the three factors, i.e., tumbling process, cooking temperature and cooking time, had an impact on the lightness (L*) values of meat, which increased from the minimal value of 51 at 50 °C/1 h to the maximal value of 63 at 60 °C/4 h, thus confirming findings of earlier studies [27,35,40]. However, the effects of tumbling and cooking time on L* values were limited at higher cooking temperatures, especially at 80 °C where the differences in L* were less than 2 units, regardless of the meat sample analysed. These results converge with those obtained by Li et al. [54] who showed that the tumbling process did not affect the colour parameters (L*, a*, b*) of a pork ham for cooking temperatures in the range 76°C–96°C. The increase of lightness values after tumbling observed here (Table 2), especially between 50 °C and 60 °C, could be explained by the structural modification of meat near the surface that could influence the scattering, transmission, reflection and absorption of light during colour measurement [56].

Increasing the cooking temperature led to a reduction in a* (redness) values from about 13 at 50 °C to just a little over 2 at 80 °C (Table 2). The effect of cooking time was particularly pronounced at 60 °C, with a 30% reduction in a* values, as already shown by Botinestean et al. [55] on beef SM muscles cooked under vacuum at 64°C for cooking times ranging from 120 to 270 min. According to the literature, the redness intensity of cooked meat is determined by the denaturation of myoglobin which starts between 55°C and 65°C [29]. These results are in accordance with those obtained by Sánchez del Pulgar et al. [40] on pork cheek samples and Vaudagna et al. [57] on beef ST muscles. On pork, which is a meat that is a priori less red than beef, Becker et al. [35] showed that there was no statistical effect of temperature and cooking time on a* values, although a* values tended to decrease with increasing temperature. They attributed this limited effect of cooking temperature on a* to the narrow range of variation in temperature levels (53°C–58°C) tested in their study.

Increasing cooking temperature also led to a reduction in b* (yellowness) values. The reduction was even stronger when the cooking time was also increased, except at 80 °C for tumbled meat samples where the variation in the b* value was not statistically significant (Table 2). These results were globally in accordance with Yancey et al. [58] who found that b* values decreased when the end-point cooking temperature of ground beef patties was increased from 65.5°C to 76.6°C. They attributed these observations to the denaturation of myoglobin, which increased with the increase in cooking temperature and thus the mean temperature inside the ground beef patties. In contrast to these results, Botinestean et al. [55] recently found that increasing cooking times led to an increase in b* values in beef meat. However, the b* values we obtained were higher than those reported in other studies investigating sous-vide cooking [27,35,36,38,39].

Table 2 shows that chroma values (C*) decreased by almost 40% as the temperature and cooking time increased. Conversely, hue values (H*) increased by over 43%, from a minimum value of 57.7 obtained on non-tumbled meat cooked at 50 °C/4 h to a maximum value of 82.6 obtained on non-tumbled meat cooked at 80 °C/1 h. C* values were higher for the meat pieces cooked at 50 °C and 60 °C than those cooked at 80 °C, whereas H* values were lower for meat pieces cooked at 50 °C and 60 °C than those cooked at 80 °C (Table 2). These results confirmed those reported by Sánchez del Pulgar et al. [40] on pork cheek samples and by Bhat et al. [27] on beef meat. All these authors observed higher C* values and lower H* values in meat samples cooked at 60 °C compared to samples cooked at 80 °C.

Consumers' assessments of the degree of cooking are often inconsistent when based on the meat colour [59]. Nevertheless, we have shown here that tumbling followed by cooking the meat pieces at 50 and 60 °C for 4 h led to an increase in luminance values without much change in a* and b* values. These observations are due to structural changes in myofibrillar and sarcoplasmic proteins, which contributed to the increase in light scattering [56]. In general, these meat pieces could be more appreciated by consumers, as meat products with a lighter colour have good acceptability by consumers [60].

5. Conclusions

Combining tumbling of bovine ST muscles for 12 h with sous-vide cooking at temperatures in the range of 50 °C–80 °C for 1 h and 4 h improved the tenderness of meat by 20%, on average. This result demonstrates that the reduction in toughness already observed through compression tests on raw beef following tumbling still persists after subsequent cooking. In detail, the shear force values of the non-tumbled meat pieces cooked at 50 °C increased significantly when the cooking time was increased from 1 h to 4 h. However, there was no significant difference in shear force values between tumbled meat pieces cooked at 50 °C for 1 h vs. 4 h. Vacuum cooking the meat pieces at 60 °C and 80 °C led to a more than 40% reduction in shear force values compared to cooking at 50 °C. Cooking losses increased with increasing temperature and cooking time, and were lower in the case of tumbled meat pieces compared to non-tumbled meat pieces. This is probably due to the weight losses that occurred during tumbling, which have not been considered in the overall calculation of cooking losses. Tumbled meat pieces cooked at high temperatures (60 °C and 80 °C) had higher lightness values than those cooked at 50 °C, and all colour parameters were generally influenced by both cooking time and temperature. Combining 12 h of tumbling with sous-vide cooking at temperatures close to 60 °C, therefore, appears to provide the best compromise between improving the tenderness and limiting the cooking losses of low-value beef meat cuts. The combined effects of tumbling and sous-vide cooking on sensory quality and consumer acceptance of mechanically-tenderized meat pieces warrant further investigation using sensory analyses realized by tasting panels. However, the results obtained in this study could be used to develop new pre-cooked meat products that are tender from pieces of lower economic value usually processed into minced steaks. Combining tumbling with marinating, could lead to a new range of marinated and tenderized products.

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