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Finite Element Formulation of Over-Milking Process on Bovine Teats at Different Size with Linear Elastic Properties

Hülya ÖZ[1], Adnan DEĞİRMENCİOĞLU[2], Hamdi BİLGEN[2]
[1]Ege University, Vocational Training School, Agricultural Machinery Program, 35100, Bornova- İzmir
[2]Ege University, Faculty of Agriculture, Department of Agricultural Machinery, 35100, Bornova-İzmir
hulya.oz@ege.edu.tr

Summary: This is intended as an interim report of the findings obtained from the simulation based study on teats using Finite Element Method (FEM). The objective of this study was to simulate teat behavior during milking phase in machine milking and to find out the differences or similarities in stresses and displacements as a result of variable teat size with linear elastic properties using finite element method. For this purpose, fresh excised teats obtained from a private company were investigated from the point of their dimensions in order to create models for the simulations. The teats considered for the simulations were 40, 60 and 80 mm long and they were assumed to be conical in shape and half of the teats were modeled in 3-D assuming the teats are symmetrical around longitudinal (y) axis. The simulations were carried out in software called "Marc". It was also assumed that there exists no-milk in teats and as a result of this assumption, the study became the simulation of over-milking process which has critical importance from the point of udder health. The necessary boundary conditions to the teats were assigned and the linear elastic behavior of the teats was simulated. Based on the results obtained from the simulation based study, it was concluded that the differences in length did not alter the level of normal and shear stresses in teats but the displacements especially in longitudinal axis changed.
Key words: Teat size, machine milking, stress, strain, displacement, finite element method

Lineer Elastik Özelliğe Sahip Farklı Büyüklükteki İnek Meme Başlarında Aşırı Sağım İşleminin Sonlu Elemanlar Yöntemi Formülasyonu

Özet: Sonlu Elemanlar Yöntemi'nin kullanıldığı ve inek memelerinde simülasyona dayalı bu çalışma, elde edilen bulguları içeren bir dizi çalışmanın ara raporu niteliğindedir. Çalışmanın amacı, makinalı sağımın süt alım safhasında farklı büyüklüklerde ve lineer materyal özelliğine sahip memelerde oluşan gerilme ve yer değiştirmelerdeki farklılık veya benzerlikleri Sonlu Elemanlar Yöntemi'ni kullanarak simüle etmektir. Bu amaçla, özel bir şirketten elde edilen meme başları, simülasyonu gerçekleştirmek üzere modellerinin oluşturulması amacıyla boyutları açısından incelemeye alınmıştır. Simülasyonlar için düşünülen meme başları; 40, 60 ve 80 mm uzunlukta olacak şekilde, konik biçimde ve düşey düzlem boyunca simetriklik gösterdikleri varsayımıyla 3 boyutta modellenmiş ve modellemede uzun eksende kesiti alınan yarıları esas alınmıştır. Simülasyonlar, "Marc" adı verilen bir programda gerçekleştirilmiştir. Simülasyonlarda meme başı içerisinde sütün olmadığı varsayımı yapılmış ve bu varsayım sonucu çalışma, inek memelerinde aşırı sağım işleminin simülasyonu olarak gerçekleştirilmiştir ki bu sağım meme sağlığı açısından kritik bir öneme sahiptir. İnek meme başlarına gerekli sınır değerleri atanmış ve lineer elastik davranışları simüle edilmiştir. Simülasyon esasına dayalı bu çalışma sonuçlarına göre, uzunluk farklarının meme başlarında normal ve kayma gerilmeler açısından büyük bir farklılık yaratmadığı, ancak özellikle düşey eksende yer değiştirmelerin önemli düzeyde olduğu sonucuna varılmıştır.
Anahtar kelimeler: Meme büyüklüğü, makinalı sağım, gerilme, birim uzama, yerdeğiştirme, sonlu elemanlar yöntemi

INTRODUCTION and LITERATURE REVIEW

The complexity of machine milking in terms of variables affecting the teat load has been the main issue in many studies conducted. The variables affecting machine milking can be examined in two parts. One is machine related variables and the other one is teat related variables. The most important machine related variables could be stated as the level of vacuum applied, pulsation characteristics, the liner properties and the age of the liner.

The teat related variables could be the size and the stiffness of the teat. An additional condition to the machine milking could be the one that is operation related. This means that the interaction or harmonious action of rubber and the teat. In addition to the main effect of these factors in milking, their interaction is of importance in order to increase the milking efficiency since inharmonious action will cause a reduction in milk yield and udder health of herd. Finally, this situation may also result in problems related to herd management.

Theoretically, milk within the teat acts as a cushion against the collapse of the teat liner and prevents frictional irritation to the epithelial lining of the teat cistern. Conversely, collapsing action of liners on empty teats is injurious (Peterson, 1964). The process of milking from empty teats is called "over-milking" and this situation usually occurs due to improper milking machine use and this is accepted to be the key factor in machine-induced mastitis. The effects of improper milking machine use on teat condition and mastitis incidence were stressed in many studies, mostly experimental and at this point the reader is referred to read these studies conducted by Peterson, 1964; Hamann, 1985; Ingalls, 2000; Hillerton *et al*., 2002; Mein *et al*., 2003 in order to have a better understanding of this phenomena.

In addition to the experimental studies, the simulation based studies, on the other hand, may help to understand how and where the deformations and critical stresses occur in a teat.

One of the simulation tools in engineering applications is Finite Element Method (FEM) and the literature search revealed that some studies were conducted by Balthazar(1978) and Toth *et al.* (2000) using FEM. In their study, Toth *et al.* (2002) applied finite element method to milking problem to analyze milk and cleaning liquid flow computation while the study by Balthazar was conducted with 1970's computer technology and did not include size effect on teat deformations, stresses and strains. Today's technology allows to make the computations faster and to investigate the many aspects of the phenomena deeply. The recent studies conducted by Harty *et al.* (2004) and Degirmencioglu *et al.* (2005) focused on milk flow simulations and simulation of over-milking process on bovine teat using finite element analysis. Harty *et al.* (2004) developed a model to study the response of a liner to study the changes in composition, geometry, tension and differential pressure. Degirmencioglu *et al.* (2005) worked on bovine teat behavior under different type of loading during milking phase and found the strains and stresses in teat. They concluded that the teat canal where the some maximum stresses occur is a critical location. On the other hand, our literature search indicated that no study that includes the effect of teat size on deformations and stresses is available. Hence, a study was conducted and the objective was to investigate the variable linear elastic parameters of teats at different sizes on stress distribution in a teat in milking phase during over-milking process.

MATERIAL and METHOD

In order to study the teat behavior under load, the teats with a length of 40, 60 and 80 mm were considered and modeled in a finite element program called Marc*. For this purpose, excised teats obtained from a private company were investigated from the point of their dimensions. The scaled photos of the teats were taken and their 2-D drawings were sketched on paper and then the coordinates of teats were obtained and defined in the program in 2-D. The 2-D meshed teat structures were then converted into 3-D for studying the behavior of variable size teats at 40, 60 and 80 mm long. An example of an excised teat and the 3-D meshed view of the teat used for simulations are shown in Figure 1.

The thickness of the teat wall was in the neighborhood of 10 mm. The diameter and the length of the teat canal were 1 and 10 mm, respectively. The modulus of elasticity (E) and Poisson's ratio (ν) values as stated by Davis *et al.* (2001) were used in simulations. The modulus of elasticity of 124 kPa was selected. This was the maximum limit of the modulus of elasticity values given by Davis *et al.* (2001). Poisson's ratio was assumed to be 0.45 and this was the minimum value as reported by Davis *et al.* (2001).

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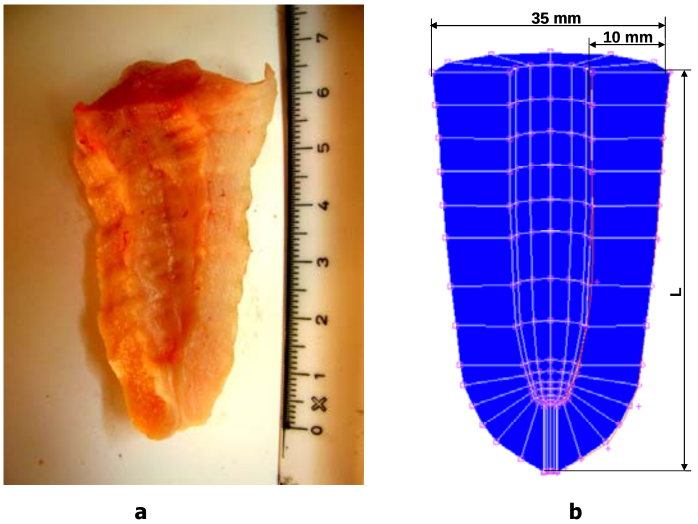

Figure 1. a) General view of an excised teat, b) meshed view and dimensions of the teat simulated

Finite Element Formulation of the Problem

The finite element is a general method of structural analysis in which a continuous structure is replaced by a number of elements interconnected at a finite number of nodal points. This study uses the finite element method to obtain displacements and stresses to simulate teat behavior when subjected to vacuum or negative pressure and find out the differences as a result of varying size. The problem was studied in 3-D assuming that the applied loads lie in the x-y-z plane.

The finite element analysis consists of the following basic operations;

1. Development of stiffness matrix of an arbitrary element with respect to local co-ordinate system,
2. Transformation of the element stiffness from the local co-ordinate system to a global co-ordinate system of the complete structural assemblage,
3. Superposition of individual element stiffness to obtain the total stiffness matrix of the total system,
4. Formulation of equilibrium equations relating the applied nodal forces and resulting nodal displacements and their solution,
5. Computation of element stresses resulting from the computed nodal displacements making use of the element stiffness matrices.

The 3-D shape of the teat modeled in the simulation program included 60, 84 and 102 hexagonal elements associated with 154, 210 and 252 nodes for the 40, 60 and 80 mm long teats, respectively. Some assumptions were made for the simulations. It was assumed that the teat is symmetrical around the longitudinal axis (y) and the same modulus of elasticity and Poisson's ratio were defined for the elements. It was assumed that there exists no-milk in teat for the sake of simplicity. As a result of this assumption, this study became the simulation of over-milking process. The weight of the teatcup and teat were ignored for the simulations.

The necessary boundary conditions assigned in order to carry out the over-milking simulation in teat are as follows. The boundary conditions imposed were: the nodes on the top of the teat were fixed in x, y and z direction while the nodes at the symmetrical axis were fixed in z direction only. Face load was defined on the faces of the elements that surround the teat and this was achieved as vacuum of 50 kPa.

Loading on teats at different size was simulated separately and from the simulations, the displacements and stresses were obtained. The peak values of stresses, strains and displacements and their locus were also determined.

RESULTS and DISCUSSION

The simulated behaviour of the teat was first examined in terms of the correctness of the model developed in the simulation program. For this reason, the study conducted by Pier *et al.* (1956) was used to compare the behaviour of the teat in milking phase (Figure 2).

As seen from Figure 2, the radiograph and the simulated view of the teat in milking phase show similarities. At a certain point of the upper part, a neck forms and the whole teat is also pulled downward. This means that the teat is displaced in longitudinal direction. During this phase, it is expected that the teat canal also enlarges. It could be stated that the enlargement of teat canal is similar for the all sizes. This means that the teat canal diameter becomes 1.92 mm on the top of the teat canal while the diameter is 1.12 mm on the bottom part of the teat for all sizes. The displacements in teat canal are given in Table 1.

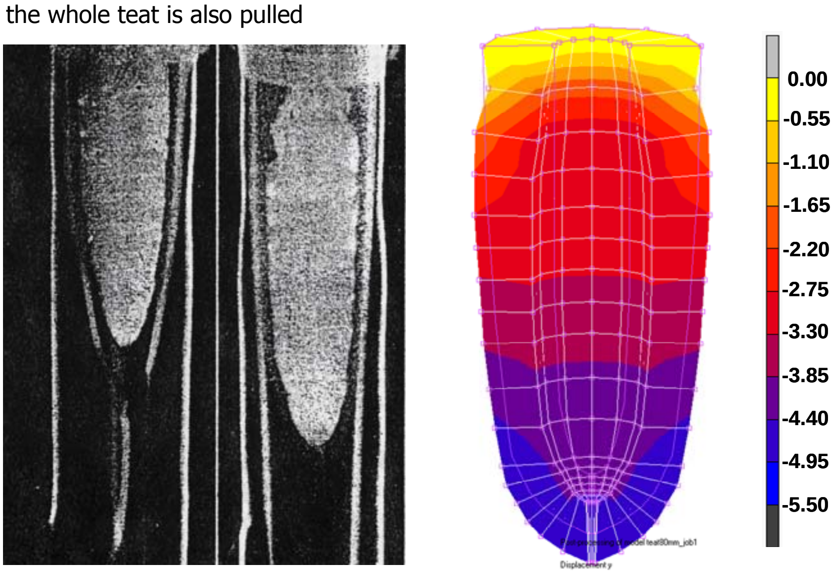

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Figure 2. Radiograph view of a teat (from Pier *et al.*, 1956) in massage a) and milking phase b) and simulated displacements, mm c) in longitudunal direction in teat in milking phase for 80 mm long teat (the scale on the right of the simulated teat is in mm)

Table 1. Displacements (mm) in teat canal

Teat length (mm)	Direction					
	x		y		z	
40	0.06*	0.46**	-2.58	-2.77	-0.06	-0.46
60	0.06*	0.46**	-3.43	-3.64	-0.06	-0.46
80	0.06*	0.46**	-4.58	-4.79	-0.06	-0.46

*: at lower part of the teat canal **: at upper part of the teat canal

The displacements in all directions in whole teat are given in Table 2 with respect to teat length. As seen from the table the displacements in whole teat changed significantly especially in longitidunal axis as the teat length was increased from 40 mm to 80 mm.

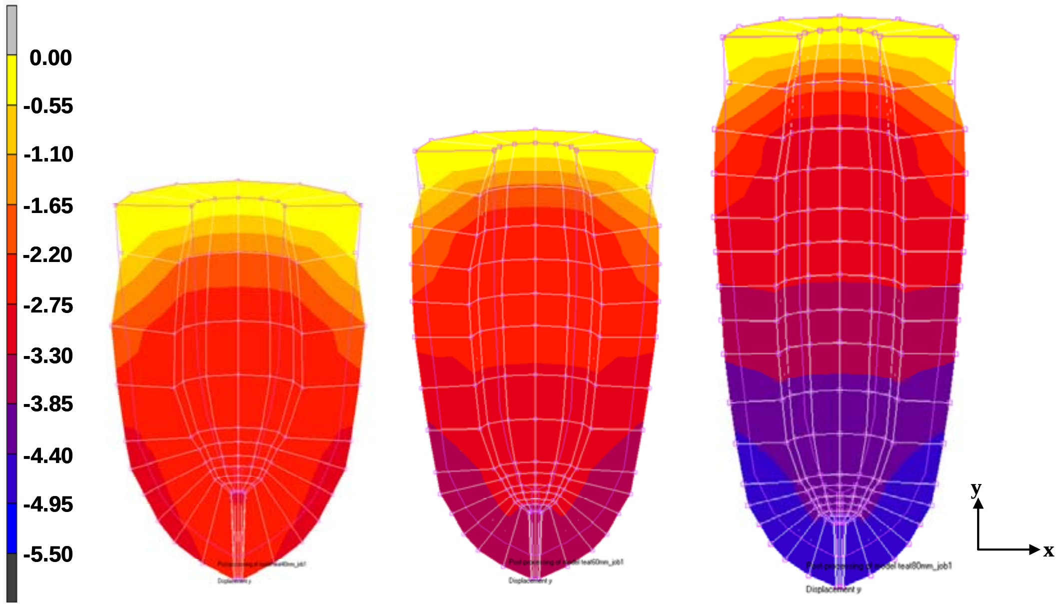
Table 2. Displacements (mm) in whole teat

Teat length (mm)	Direction			
	x	y	z	
40	±3.0	-3.01	-3.03	0.46
60	±3.6	-3.81	-3.61	0.63
80	±3.6	-4.97	-3.60	0.75

Teats are displaced 3.01, 3.81 and 4.97 mm for 40, 60 and 80 mm long teat, respectively. The visual representation of this finding is depicted in Figure 3.

The normal and shear stresses obtained from the simulations are given in Table 3 and 4, respectively. As seen from the tables, the normal and shear stesses did not show significant differences as the teat length changed. The interesting finding was that the maximum normal stress σ_x always occurred in teat canal. The visual findings of normal stresses are shown in Figure 4.

In general, the results obtained from this simulation based study indicated the teat canal is a critical point in terms of some normal and shear stresses once the teat is subjected to over milking. This result could be a good explanation how much an over milking process is injurious to the teat and also for the widespread use of automatic cluster removers since their use has significantly reduced over milking.



a b c

Figure 3. Displacement contours in longitudunal direction for a) 40 mm; b) 60 mm and c) 80 mm long teat (the scale on the left is in mm)

Table 3. Normal stress range (N mm^{-2}) in whole teat

Teat length (mm)	σ_x		σ_y		σ_z	
40	1.62×10^{-2}	7.54×10^{-2}*	3.26×10^{-2}	8.08×10^{-2}	10.3×10^{-3}	9.42×10^{-2}**
60	1.31×10^{-2}	7.47×10^{-2}*	3.07×10^{-2}	7.95×10^{-2}	6.01×10^{-3}	10.0×10^{-2}**
80	1.34×10^{-2}	7.33×10^{-2}*	3.58×10^{-2}	7.67×10^{-2}	6.35×10^{-3}	9.97×10^{-2} **

*: Max value in teat canal**: Max value at outer surface of the teat canal

Table 4. Shear stress range (N mm^{-2}) in whole teat

Teat length (mm)	τ_{xy}	τ_{xz}	τ_{yz}	
40	$\pm4.06\times10^{-3}$	$\pm 1.14\times10^{-2}$	-4.06×10^{-3}	2.08×10^{-3}
60	$\pm3.11\times10^{-3}$	$\pm 1.33\times10^{-2}$	-2.91×10^{-3}	3.11×10^{-3}
80	$\pm 2.95\text{x}10^{-3}$	$\pm1.29\times10^{-2}$	-2.95×10^{-3}	$2.38\text{x}10^{-3}$

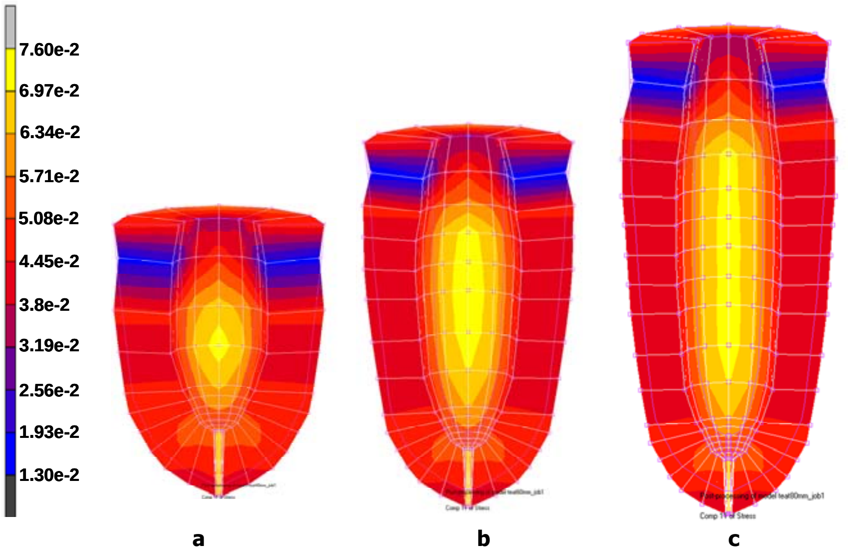


Figure 4. Normal stresses (σ_x) contours for a) 40 mm; b) 60 mm and c) 80 mm long teat (the scale on the left is in N mm^{-2})

CONCLUSIONS

The following conclusions were drawn from the study:

1. Teat length did not affect the level of the normal and shear stresses induced on teats.
2. The displacements depending upon the teat size changed significantly in longitudunal axis but the enlargement of teat canal was similar for all teats.
3. Teat canal is a critical point in teat since it is subjected to some maximum normal and shear stresses during over-milking process.

FUTURE STUDIES

The authors are in continuing effort in order to reveal much of the information about teat deformations and stresses using finite element method and the next step is to simulate teat and liner as they interact with each other in milking and massage phase. The differences in terms of stresses and strains will also be explored in this future study with or without the existence of milk in teat.

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