Journal of Engg. Research **Vol. 2 No. (4) Dec 2014** pp. 87-101

تقدير الخواص الميكانيكية للأنسجة الرخوة عند تعرضها للإصطدام الديناميكي

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الخلاصـة

الأنسجة الرخوية للإنسان تمتاز بالليونه وعدم التجانس مما يؤدي إلى صعوبة في تقدير خصائصها الميكانيكية، ولذا تهدف هذه الدراسة لمعرفة الخصائص الميكانيكيه للأنسجة البشرية عندما تكون تحت تأثير الإصطدام الديناميكي مما يمكن الاستفادة من تطبيقاتها في عدة مجالات، وقد أصبح للخصائص الميكانيكية لهذه الأنسجه اللينه أهميه متزايده في البحوث الطبية الحيوية وكذلك علوم الجريمه، بالإضافه إلى ذلك فإن معرفة هذه الخصائص الميكانيكية يمكن الإستفاده منها في عمل محاكاة للعمليات الجراحية الواقعية، والتخطيط قبل الجراحة ، والإجراءات الطبية بمساعدة الروبوت وأيضا يمكن الإستفاده منها في استخلاص الخصائص اللازمة لتأثير الكدمات لأغراض الطب الشرعي وعلم الجريمة.

وتم تقدير خصائص التخميد لأنسجة الإنسان باستخدام نظام يتكون من زنبرك و كباس. ويمثل معامل الثبات للزنبرك بالرمز (k) ويمثل معامل الثبات للكباس بالرمز (C). وقد تم جمع البيانات من خلال تعريض خلايا الإنسان الرخوة في منطقة الكتف لضربات فعليه بإستخدام البندول بمستويات مختلفة من الأوزان والطاقة والسرعة. عند إجراءعملية تحليل النتائج تم تكييف البيانات وإزالة الفروقات البشريه مما أدى إلى نتائج أكثر إيجابيه لمعرفة معامل الثبات للزنبرك (k) ومعامل الثبات للكباس (C).

وفي الختام، أظهرت النتائج التي تم جمعها من التجارب البشريه أن كلا من صلابة ومقاومة الملطف ترتبط إلى حد كبير مع كتلة البندول (الجسم الصادم) وطاقتة وسرعته ومعرفة خصائص الأنسجة البشرية يمكن أن تستخدم في تحديد مكان وقوة الضربه اللتي تعرض لها الضحيه لمساعدة في تحقيقات الأدله الجنائيه عند المعاينه ومعرفة تفاصيل الجريمه أو الحادث عند وجود آثار للكدمات.

Estimation of mechanical properties of soft tissue subjected to dynamic impact

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ABSTRACT

Human soft tissue is highly deformable leading to a difficulty in estimating its mechanical properties. This paper focuses on the extraction of human tissue dampening properties under dynamic impact, which enabled an efficient implementation of mechanical response of tissue, which is of growing interest and importance in biomedical research and forensic science. Such properties are not only useful for realistic surgical simulation, preoperative planning, and robot-assisted medical procedures, but also may be useful in deriving impact characteristics necessary to cause contusions for forensics purposes. The estimates of the damping properties of human soft tissue was done by using spring and damper system as a model; mass-damper-spring (MDS). Spring stiffness is represented by the spring constant K and dashpot damping resistance is represented by the damper constant C. Data were collected by striking human subjects with a weighted pendulum at different levels of energy, velocity, and mass. The estimation process involved conditioning the data, such that the modeling process and estimation were feasible, resulting in estimates of K and C. In conclusion, using impact data collected on living human tissue to estimate the dampening properties is plausible. The results showed that both the stiffness and the dampening resistance are highly correlated with the mass of the striking object, its energy and velocity. Hence, knowledge of these properties may be used in determining the impact parameters required by a striking object, which might be helpful in forensic investigation when contusions were induced.

Keywords: Dampening; green's function; pendulum; soft tissue.

INTRODUCTION

In the era of medical technology advancement, development of deformable models for simulation of live tissue plays an important role in virtual surgical simulation (Otamendi, 2011). In addition, mechanical characterization of alive human tissue properties is a necessity to predict the tissue deformation, when the tissue is subjected to external forces and displacement which may be used in forensic investigation (Kerdok, 2006), (Desmoulin & Anderson, 2011).

Dampening properties of live human tissue are rarely found (Desmoulin & Anderson, 2011). Modeling of tissue of live human can lead to the development of more realistic estimates of tissue properties and to a better designing of surgical simulators. Such simulators can generate realistic human anatomy, physiological responses that can assist teaching and provide an objective assessment of skills. Using medical simulators, students can practice on a variety of complex cases and receive detailed feedback on their performance. Patient safety is not compromised, while the student is learning. In addition to training health care professionals, surgical simulation systems are also useful for pre and intra-operative planning of medical interventional procedures. Similarly, contusions being used as evidence in a criminal matter can contribute to the conviction or exoneration of a suspect (Desmoulin & Anderson, 2011). If the impact characteristics could be derived from the tissue, we could gain insight helpful in forensic investigations and to assist in making decisions. Hence, tissue properties may help clinicians and investigators to increase accuracy of the surgical procedure, minimize patient trauma, and make accurate conclusions about criminal investigation.

This research creates a method for estimating the dampening characteristics of the tissue of the deltoid area of human subjects using a mass-damper-spring model as the theoretical model and presents the estimates from impact data gathered on living human subjects. A mass-damper-spring system was assumed to represent the mechanical characteristics of human tissue subjected to impact. Spring stiffness was represented by the spring constant K and dashpot damping resistance was represented by the damper constant C. Data were collected by striking human subjects with a weighted pendulum at different levels of energy, velocity, and mass (Alkhaledi, 2010). Dynamic measurements that were made during the impacts were used in the estimation process. The estimation process involved conditioning the data such that the modeling process and estimation were feasible resulting in estimates of K and C. Correlation and stepwise regression analyses were used to study the trends of the numerical estimates obtained of damping characteristics K and C.

Chen *et al.* (1996) used ultrasound to identify the elastic behavior of the tissue. Yeh *et al.* (2001) estimated the Young's modulus for a healthy and diseased human liver. Tension properties were examined in order to identify the mechanical properties of the human soft tissue (Miller, 2001). The findings of those studies were that soft tissue was not only an elastic material but also a visco-elastic material. Fujii (2005) and Daly (1982) attempted to apply mechanical models as a representation of human tissue and their findings were that mass-spring-damper (MSD) models can be applied to human tissue as well as the human body as one entity. Nedel & Thalmann (1998), Ji & Bell (2008), used the idea of modeling the human body as MSD model and their results were encouraging that these models are applicable. Maurel *et al.* (1998), Finlay (1969), Manschot (1985) and Wiley (2007) applied these models on human tissue and their findings confirmed that human soft tissue is a viscoelastic and its mechanical behavior is not linearly consistent.

The objective was to estimate the dampening constants for the deltoid area of human subjects based on impact to that area of the human body under different levels of energy, velocity and mass of the impacting object. The estimation methodology used in this research functioned under a number of assumptions. They were that there is a valid deformation curve; the impacted material was homogenous. The reaction due to the impact was the same throughout its depth; the impacted material was stationary, the impacted tissue were healthy; the subject had the same health condition in all trials, the impacted material had the same consistency for each trial, and the impacted material had sufficient thickness that the penetration of the pendulum was constrained only by that material. The modeling methodology functioned under the assumption that the model used consisted of a parallel set of one damper and one spring and was appropriate.

METHOD

This research used a portion of the data that were described in detail in Alkhaledi (2010). Subjects were exposed to minor impacts to the deltoid area of the shoulder, administered by a pendulum. The pendulum was instrumented with a load cell and accelerometer to monitor impact and motion during impact. The apparatus consisted of data collection system connected to PC, a pendulum with specifically designed weights, a load cell with a capacity of 25 pounds mounted to the pendulum and connected to the data logger to record forces, and an accelerometer mounted at the top of the pendulum and was connected to the same data logger. FLIR thermal imaging camera was used to monitor impact area and thermal characteristics of the impacts. The thermal camera was connected to PC (see Figure 1).

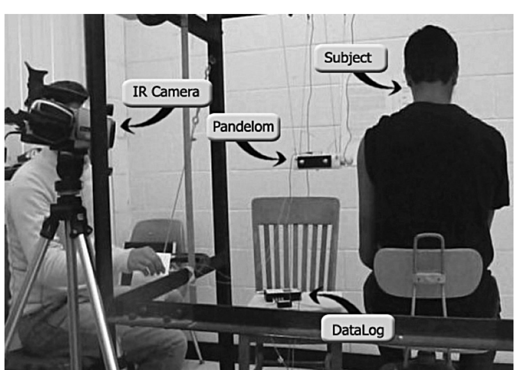

Fig. 1. Experimental equipment setup with a subject next to equipment. (Alkhaledi, 2010)

Energy, velocity, and size of the spherical striking object were independent variables. Physical measurements of force vs. time and acceleration vs. time were recorded simultaneously, as the pendulum impacted the subject. The position of pendulum during impact was derived from acceleration vs. time data.

Energy (E) was set at 3 levels of 0.75, 1.125, and 1.5 joules. Velocity (V) was set at 3 levels of 1.25, 1.5, and 1.75 m/s. To achieve the desired energy and velocity levels, mass (M) and starting height levels were adjusted. The impacting objects were wooden balls mounted on the front of the pendulum and had 3 different sizes 0.0254, 0.0318, and 0.0381 meters in diameter. A random sample of five male and five female subjects, ranging in age from 21 to 35, were recruited. Anthropometric measures were taken for each subject, by using a dial caliper to measure a skin-fold thickness on the upper arm at the impact area of the surface of the deltoid muscle; muscle thickness, and bone thickness were also taken for each subject (see Table 1).

Table 1. Subject's anthropometric measures for five males and five females.

Subject	M	M	M	M	M	F	F	F	F	F
Skin-Fold Thickness (CM)	0.8	1.1	0.9	0.5	0.8	0.8	0.9	0.8	1.4	1.2
Muscle Thickness (CM)	3.3	4	3.3	2.7	3.2	3.5	2.2	2.7	4.9	2.8
Bone Thickness (CM)	4.2	5.9	4.5	3.7	5	4.1	5.6	4.9	5.1	5.3

Not all of the data collected was used for these analyses. The analyses conducted in this study were limited to the 90 data points for the impacting subject for only those trials using the 0.0318 meter balls. The trials involved three levels of energy and three levels of velocity for nine combinations for each of the 10 subjects. There were nine different pendulum masses used in order to achieve the appropriate energy and velocity combinations.

PROCEDURE

Data of acceleration were integrated twice in order to obtain the displacement data. Integrating the acceleration curve resulted in a velocity curve. Integrating the velocity curve resulted in the displacement curve. The acceleration data were numerically integrated using a time interval of 0.0001 second.

The principles of time series analysis were applied to the displacement data, in order to obtain a discrete second order autoregressive model. This was done by running the data of displacement in the data-dependent-system (DDS) program, by which the variables of a discrete second order autoregressive model were obtained - ARMA (2.1). The discrete second order autoregressive model was converted into a continuous second order autoregressive model A(2) by using the assumption of equal auto covariance, and the concept of the Green's function. As a result, a continuous second order autoregressive model was obtained. The principles of a mass-spring-damper system analysis were then applied to the A(2) model to estimate the physical characteristics of both the damping ratio and the natural frequency. For each combination of energy, velocity, and mass, the spring constant and damper constant were estimated.

Trends of these variables were studied under the different levels of external impact stimuli of energy of the impact, velocity of the impact and the mass of the impacting pendulum. Correlation analyses were conducted for estimates for each of the 90 data points and then for the nine experimental conditions averaged over the ten subjects. Subsequently, stepwise regression analyses were conducted for the estimates of K and C with energy, velocity, mass, skin-fold thickness, muscle thickness, bone thickness, and skin-fold plus muscle thickness as the available independent variables. The second and third order terms for the first three variables were also available as independent variables.

RESULTS

The dampening constants K and C for the deltoid area of human subjects based on impact to that area of the human body under different levels of energy were estimated. FLIR thermal imaging camera helped to locate the exact measured impact area (see Figure2).

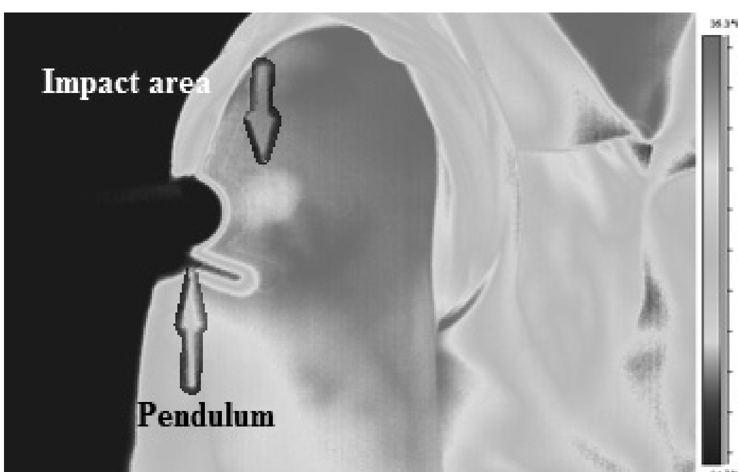

Fig. 2. Thermal image showing the measured impacted area. (Alkhaledi, 2010)

The averaged resulting estimates of K and C are presented in Tables 2 and 3. Overall the estimated values of the spring constant, K vary from 8.833 to 32.172 kN/m with a range equal 23.339 for the 90 trials. The value of damper constant, C, varied from 0.122 to 4.626 kN.s/m with a range equal 4.504 for the 90 trials. The K values averaged over subjects for each trial, varied from 9.414 to 31.632 kN/m, with a range of 22.218, as compared to the range of the individual values of 23.339. The C values averaged over subjects for each trial varied from 0.904 to 3.557 kN.s/m, with a range of 2.6535, as compared to that of the individual values of 4.626.

Table 2. Average data with regard to spring constant K.

Trial	**Energy** J	**Velocity** m/s	**Mass** Kg	**Average of spring constant K** kN/m	**Std Dev K**	**Range K** kN/m
7	0.75	1.25	0.666	15.975	0.497	1.294
8	0.75	1.5	0.489	11.859	0.402	1.038
9	0.75	1.75	0.375	9.413	0.429	1.126
16	1.125	1.25	1.000	23.75	0.192	0.565
17	1.125	1.5	0.734	18.068	1.977	1.977
18	1.125	1.75	0.562	13.892	0.765	1.970
25	1.5	1.25	1.333	31.631	0.208	0.673
26	1.5	1.5	0.979	23.493	0.3968	1.319
27	1.5	1.75	0.750	18.143	0.677	2.360

Table 3. Average data with regard to damper constant C.

Trial	**Energy** J	**Velocity** m/s	**Mass** Kg	**Average of damper constant C kN.s/m**	**Std Dev C**	**Range C kN.s/m**
7	0.75	1.25	0.666	1.392	0.519	1.364
8	0.75	1.5	0.489	0.989	0.395	1.152
9	0.75	1.75	0.375	0.903	0.561	1.943
16	1.125	1.25	1.000	2.730	0.547	3.105
17	1.125	1.5	0.734	1.648	1.009	3.292
18	1.125	1.75	0.562	1.081	0.645	2.086
25	1.5	1.25	1.333	3.557	0.470	1.716
26	1.5	1.5	0.979	2.293	0.526	1.753
27	1.5	1.75	0.750	1.825	1.021	2.955

The range for the average of the trial estimates for K is not considerably less than the overall range for the individual values. For C the range for the averages is almost half that of the individual values. The correlation values for K and C for all of the data are contained in Tables 4 and 5**.** For all variables considered whose correlation with K were statistically significant, correlations values ranged from + 0.997 for Mass down to - 0.024 for Skin Fold thickness.

Table 4. Correlation values with spring constant K.

Variable	Correlation with spring constant K	P-Value
Mass	0.997	0.000
Mass Seq	0.980	0.000
Energy * Mass	0.959	0.000
Velocity * Mass	0.933	0.000
Energy* Mass *Velocity	0.866	0.000
Energy	0.752	0.000
Energy Seq	0.748	0.000
Velocity	- 0.625	0.000
Velocity Seq	- 0.620	0.000
Energy * Velocity	0.369	0.000
Skin Fold	- 0.024	0.818

Table 5. Correlation values with damper constant C.

Variable	Correlation with damper constant C	P-Value
Mass	0.787	0.000
Mass Sq	0.785	0.000
Energy * Mass	0.751	0.000
Velocity * Mass	0.720	0.000
Energy* Mass *Velocity	0.665	0.000
Energy	0.567	0.000
Energy Seq	0.565	0.000
Velocity	- 0.500	0.000

The correlation values for subject-averaged data with spring constant K and damper constant C for all of the data are contained in Tables 6 and 7**.** For all variables considered whose correlation values for subject averaged data with K were statistically significant ranged from + 0.999 for Mass down to - 0.626 for Velocity. For all variables considered whose correlation values for subject averaged data with C were statistically significant ranged from + 0.985 for mass down to - 0.626 for velocity.

Table 6. Correlation values for subject averaged data with spring constant K

Variable	Correlation with the constant K
Mass	0.999
Mass Seq	0.983
Energy * Mass	0.962
Velocity * Mass	0.935
Energy	0.754
Energy Seq	0.750
Velocity	- 0.626

Table 7. Correlation values for subject averaged data with damper constant C

Variable	Correlation with damper constant C
Mass	0.985
Mass Sq	0.983
Energy * Mass	0.940
Velocity * Mass	0.902
Energy	0.710
Energy Sq	0.708
Velocity	- 0.626

Correlation analysis indicated that the estimate of both the spring constant (K) and damper constant (C) have a strong relationship with mass of the striking object. This strong correlation is presented in Figures 3 and 4.

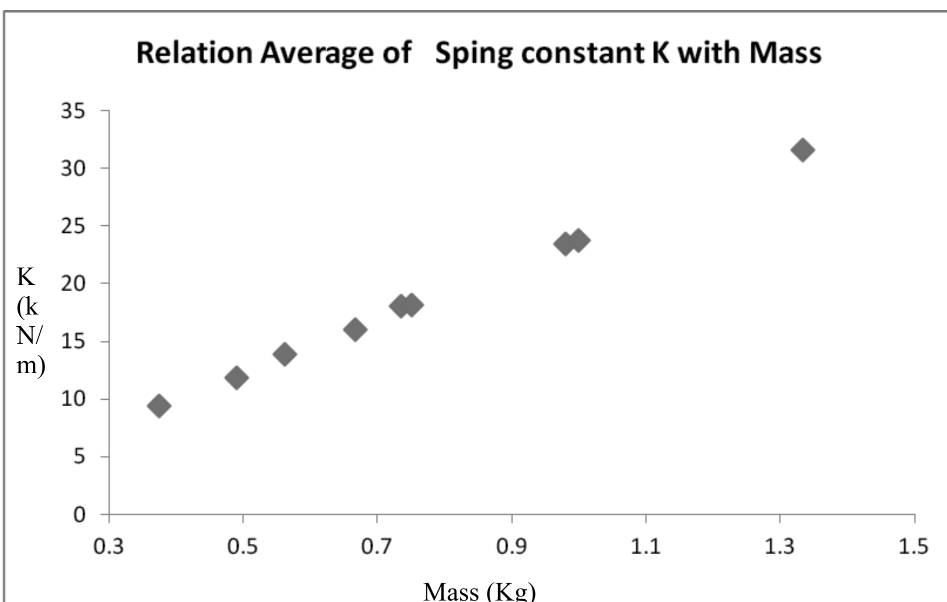

Fig. 3. Relation between the average K and mass

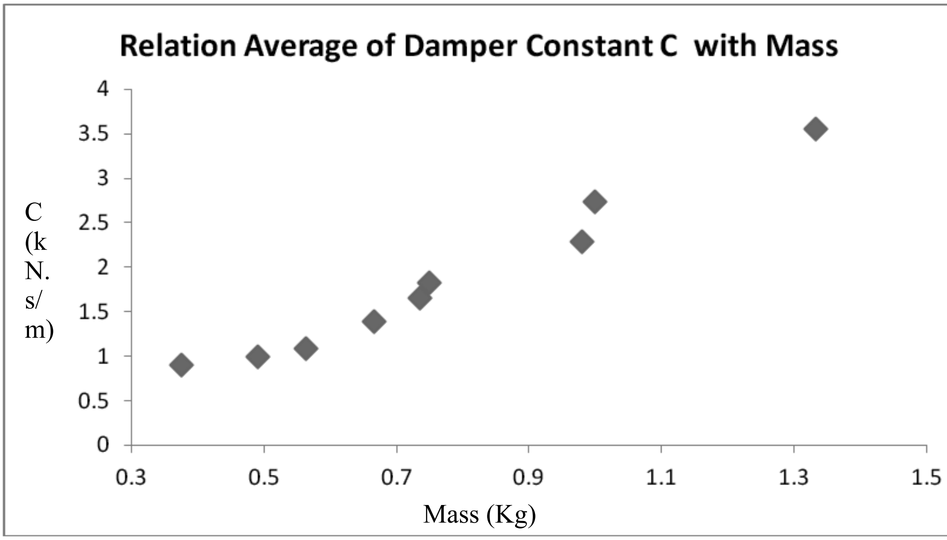

Fig. 4. Relation between the average C and mass

In addition to correlation analysis, a step-wise regression analysis was conducted. Variables that were significant for the spring constant and damper constant are contained in Table 8 which includes the model R square values.

Table 8. Variables included with the model R square values

Model Summary			
Spring Constant K		Damper Constant C	
Model	R Square	Model	R Square
1 Mass	0.994	1 Mass	0.619
2 Skin Fold Thick	0.991		

Twelve variables were available for inclusion in the step-wise analysis. Mass was significant in both spring and damper constant. Additionally, skin fold thickness was statistically significant in spring constant, K, which can be justified by the elasticity human skin has. (Daly, 1982). As a result, when skin thickness increases, it is expected to see an increase in spring constant. Step-wise analysis confirmed that mass found to be statistically significant in both spring constant and damper constant.

The regression equations are:

$$K = + 0.695 + 23.21 \text{ Mass} + 0.0028 \text{ SFT} \qquad R^2 = 0.99$$

$$C = - 0.444 + 2.962 \text{ Mass} \qquad R^2 = 0.97$$

DISCUSSION

Spring constant – K and Damper constant – C

The 90 estimates of K had an average of 18.470, a standard deviation of 0.61 and a range of 23.339 (8.833 to 32.172 kN/m). This represents a ratio of 3.64 or a greater than threefold difference in estimates that is supposed to be estimating the same parameter, K, for the same material. When the estimated values for K were averaged for each trial, those averages had a range of 22.218 (9.414 to 31.632 kN/m). This represents a ratio of 3.36 which is still greater than a threefold difference and represents very little difference from the individual values. The masses for the individual trials were all different, so trial and mass in this analysis may not be separable.

The very wide range of the 90 estimates and the very wide range of the trial averages of these estimates are of concern. These estimates should be estimating the same parameter. The relationships between the estimates and the physical variables involved in the experimentation were examined. Mass was the variable with the highest correlation with K (0.997) and all of the five highest correlation values had mass as component. When a stepwise regression was conducted, mass and skin-fold thickness were the only variables included in the final model. Therefore, for this experimentation, the estimates were highly dependent on the mass of the impacting pendulum. This is problematic and the possible reasons for its occurrence are examined below.

The 90 estimates of C had an average of 1.824, a standard deviation of 0.65 and a range of 4.504 (from .0122 to 4.626). This represents a ratio of 37.90 or a greater than thirty fold difference in estimates that are supposed to be estimating the same parameter, C, for the same material. When the estimated values for C were averaged for each trial, those averages had a range of 2.653 (from 0.904 to 3.557). This represents a ratio of 3.936, which is still greater than a threefold difference, but not the extreme of 37.91.

The very wide range of the 90 estimates and the very wide range of the trial averages of these estimates are of concern. Once again, these estimates should be estimating the same parameter. The relationships between the estimates and the physical variables involved in the experimentation were examined. Mass was the variable with the highest correlation with C (0.787) and all of the five highest correlation values had mass as a component. When a stepwise regression was conducted, mass was the only variable included in the final model. Therefore, for this experimentation, the estimates were highly dependent on the mass of the impacting pendulum. As was the case with K, this is problematic and the possible reasons for its occurrence are examined in more detail later in this chapter.

The estimates of K and C, which represent the elastic resistance of the tissue, were found to be in agreement with the literature (Desmoulin and Anderson, 2011). Our estimate can be explained by the findings of Maurel *et al.* (1998) who did study the mechanical properties of human tissues and the relationship between stress and strain. The curve as shown in Figure 5 was divided into three stages. In the first stage (I), at low strain, collagen fiber response can be neglected and the elastin fibers are responsible for the skin stretching and the relation between stress-strain is approximately linear and the angle is very low. This implies that the elastic resistance is low when the stress applied is low.

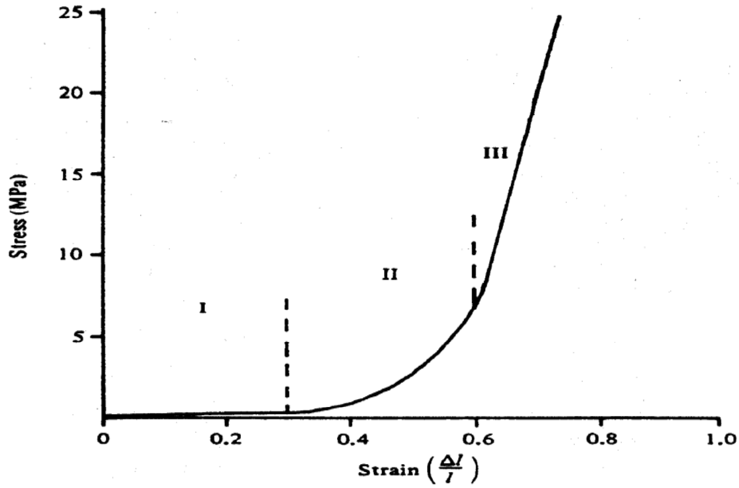

Fig. 5. Stress-strain diagram for skin showing the different stages (Maurel *et al.,* 1998).

In the second stage, (II), a gradual straightening of undulated collagen fibers causes an increase in skin tissue stiffness. Collagen fibers are the main components of the skin and they are strong and stiff. There is an intimate connection between the various skin layers. Collagen fibers are the major components of the dermis (77% of the fat-free dry weight) and form an irregular network of wavy coiled fibers, which run parallel with the human skin surface (Finlay, 1969). Collagen fibers have high strength (tensile strength of 1.5-3.5 Mega Pascal), low extensibility (rupture at strains in the order of 5-6%), and high stiffness (Young's modulus approximately 0.1 Giga Pascal (Manschot, 1985) to 1 Giga Pascal in the linear region (Maurel *et al.,* 1998).

In the third stage (III), collagen fibers are straight and are at high levels of strain. The stress-strain relationship becomes linear again but with very steep angle. This means that elastic resistance of the skin is very high when the applied stress is high.

In this investigation of both K and C, it was found that these estimates had a strong positive correlation with mass. It was found that the correlation between mass and K was 0.992 with P-value approaching zero and 0.787 with P-value is almost zero with C. These estimates represent the elastic properties of the tissue and therefore when mass increases the elastic resistance increases. When the findings of Maurel *et al.* (1998) were examined; stress was broken up into its initial component (Force /Area). Area was a fixed variable in our estimate and the force was represented by mass (F= m*a, Newton's law). As a result, it could be said that when mass increases, the elastic resistance increases and this was what the analysis of the estimate confirmed.

In phase (I) as shown in Figure 5, skin demonstrates elastic behavior, while in phase (II) and (III) skin shows visco-elastic behavior. It may be, that when the mass was relatively small, the tissue demonstrated elastic behavior in which the spring constant took most of the responsibility protecting the inner tissue, and with larger masses it appeared that the tissue showed visco-elastic behavior, which may mean that a combination of the spring and the damper were resisting the impact. It seems reasonable that the estimates of K and C were logically explaining the findings of Maurel *et al.* (1998).

The methods of analysis used to analyze the data obtained were – correlation analysis and stepwise regression. It was found that mass's relationships with both estimated values of spring and damper constants were linear as was depicted in Figures 3 and 4. As mass increased, the spring constant increased. The same was true for the damper constant. The graphs show that mass and the spring constant have an almost a perfect linear relationship (R= 0.999), and this was also true for the damper constants (R= 0.985). This might imply that the tissue did increase its elastic resistance to counter the stimuli caused by the increases in the mass of the impacting object. It is possible that the system of the underlying tissues might change their characteristics in order to absorb as much energy as it can, to prevent more penetration into the tissue to avoid damage.

Correlation analysis showed that both the spring constant, K, and the damper constant, C, were highly correlated with mass. Stepwise regression showed that mass was found to be a statistically significant predictor of both spring constant and damper constant. These results imply that mass is the most important variable affecting the estimation of the damping characteristics.

From Tables 3, 4 and 5, it was apparent that no personal factors (skin- fold, muscle, and the skin-fold plus muscle) were statistically significant for the correlation analyses, and the stepwise regression analyses. It was expected that these characteristics would affect the estimates. These results might imply that the human tissues in the area tested have similar damping characteristics regardless of the thickness of the skin or the muscle layers.

CONCLUSION

This research was conducted to study and estimate the damping characteristics of human soft tissue. Reviewing the available literature revealed that there was little knowledge regarding damping characteristics of human tissue. Utilizing the principles of a mass-spring-damper system enabled the estimation of the spring constant (K) and damper constant (C) for each trial of the experiment. Correlation and stepwise regression analyses were used to study the trends of the numerical estimates obtained of damping characteristics K and C.

Estimated constants for C and K varied from 0.903 to 3.557 and 9.413 to 31.631 respectively. No past estimates for C and K were found in the literature and hence it is not possible to determine if these estimates are reasonable or not. The estimates varied very widely, which is of concern. The possible reasons for these large variations were explored and discussed. Any of them individually, or in combination, may be responsible for this wide variation. The mass of the impacting object was the dominant variable in determining the estimates of the spring and dampening constants.

The methodology utilized to estimate the constants did not consider either the size or shape of the impacting object. This may be a shortcoming of the methodology. Estimating the dampening constants of human tissue is problematic. In reality, human tissues are not homogenous; they differ in composition and properties. They are alive and react in ways that might affect the results. In this experimentation, the subjects might have moved, anticipated the impact, or had a reflex action that changed the resulting data collected. Any of these could affect the resulting estimates. Furthermore, the depth of the tissue and the fact that it is backed by rigid material, bone, may affect the estimates and would most likely affect those situations involving the most deformation or penetration.

Finally, the tissues impacted were composed of two layers that were not consistent in thickness from subject to subject, even though this research essentially assumed homogenous material. Hence, this research represents a significant step toward quantifying the physical characteristics of living human tissue.

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Submitted: 18-02-2014

Revised: 18-02-2014

Accepted: 14-07-2014