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Original Article / *Özgün Makale*

Experimental comparison of efficiency of four different sternum closure techniques

Dört farklı sternum kapama tekniğinin etkinliğinin deneysel olarak karşılaştırılması

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ABSTRACT

Background: This study aims to compare experimentally the efficiency of four different sternal closure techniques performed using steel wire, steel cable, titanium clips and titanium plates.

Methods: In the experiments, during which artificial sternum models were used, static loadings were performed to create lateral distraction, longitudinal shear and transverse shear in the models. The methods were compared considering their allowable load (load corresponding to 2 mm displacement) and stiffness values. The costs, and ease and speed of application of the methods were also evaluated.

Results: Although the highest allowable load and stiffness values in lateral distraction were obtained in the titanium clips method, the differences in allowable load and stiffness of all methods were not statistically significant. Although the highest allowable load in longitudinal shear was obtained in the titanium plate method, the only statistical significance in allowable loads was between the steel cable method and other methods. While the highest stiffness value in this loading was obtained in the titanium clips method, the difference between this method and conventional wire methods was not statistically significant. The highest allowable load and stiffness values in transverse shear were obtained in the titanium clips method and the differences between this method and other methods were statistically significant. When the costs, and ease and speed of application of the methods were considered, the most advantageous method was the conventional steel wire method.

Conclusion: According to the results of our experiments, titanium clips displayed more stable behaviour and provided better sternal closure compared to the other methods.

Keywords: Biomechanics; median sternotomy; sternum closure methods.

ÖZ

Amaç: Bu çalışmada çelik tel, çelik kablo, titanyum klips ve titanyum plak kullanılarak yapılan dört farklı sternum kapama yönteminin etkinliği deneysel olarak karşılaştırıldı.

Çalışma planı: Yapay sternum modellerinin kullanıldığı deneylerde, modellerde yanal ayrılma, boyuna kesme ve enine kesme oluşturacak şekilde statik yüklemeler yapıldı. Yöntemler emniyet yükü (2 mm deplasmana karşılık gelen yük) ve direngenlik değerleri dikkate alınarak karşılaştırıldı. Yöntemlerin maliyetleri, uygulama kolaylıkları ve hızları da değerlendirildi.

Bulgular: Yanal ayrılmada en yüksek emniyet yükü ve direngenlik değerleri titanyum klips yönteminde elde edilmesine rağmen, tüm yöntemlerin emniyet yükleri ve direngenlikleri arasındaki farklılıklar istatistiksel olarak anlamlı değildi. Boyuna kesmede, en yüksek emniyet yükü titanyum plak yönteminde elde edilmesine rağmen, emniyet yüklerinde istatistiksel anlamlılık sadece çelik kablo yöntemi ve diğer yöntemler arasında vardı. Bu yüklemede en yüksek direngenlik değeri titanyum klips yönteminde elde edilirken bu yöntemle geleneksel tel yöntemleri arasındaki farklılık istatistiksel olarak anlamlı değildi. Enine kesmede en yüksek emniyet yükü ve direngenlik değerleri titanyum klips yönteminde elde edildi ve bu yöntemle diğer yöntemler arasındaki farklılıklar istatistiksel olarak anlamlı idi. Yöntemlerin maliyetleri, uygulama kolaylıkları ve hızları dikkate alındığında, en avantajlı yöntem geleneksel çelik tel yöntemi idi.

Sonuç: Deney sonuçlarımıza göre titanyum klipsler diğer yöntemlere kıyasla daha istikrarlı davranış sergiledi ve daha iyi sternal kapama sağladı.

Anahtar sözcükler: Biyomekanik; mediyan sternotomi; sternum kapama yöntemleri.

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Postoperative complications of median sternotomy, although it is not frequent, prolong hospitalization duration and increases morbidity, mortality and notably infection. Sternal problems might be in the form of only sternal dehiscence, superficial sternum infection might end up with osteomyelitis, costochondritis or mediastinitis.[1] Although the rate of observation of complications is around 0.5-2.5%, mortality rate is changing around 10-40%.[2]

To avoid these complications of sternotomy, a good sternal fixation is a must.[1] In general, in case that closing technique has high strength and provides sufficient stiffness, good results are obtained.[3] At the end of the studies carried out with aim of obtaining the best sternal stability, more than 40 techniques were developed and a lot of different materials were used for closing sternum.[4] However, there is no consensus yet about which method is the most appropriate for sternal closing.[4] At the selection of the method which would be used, along with the stiffness and stability the method provides, the cost and ease of application of the method is also effective. However, due to the big cost differences among closing materials, unfortunately, the cost of method becomes the most important reason for preference.

In this study, the effectiveness of four different closing methods carried out by using steel cable, titanium clips and titanium plate along with conventional steel wire method which is the most commonly applied closing method under three different loading effects was compared with static experiments. During the comparison of methods, the cost of methods, ease of application and the behaviors observed during the experiments were considered as well.

MATERIALS AND METHODS

The methods examined in this study were given in Table 1.

Using the conventional wiring method, five wires in the body (no. 5) (SERAG-WIESSNER GmbH & Co. KG. Naila, Germany) were wired in the form of peristernal, in manubrium and xiphoid zones, the wires were inserted in the form of transsternal one at a time (Figure 1a). The wires used in manubrium and xiphoid zones were applied in the same manner in all of the methods compared. In the steel cable method, the cables (Pioneer Surgical Technology, Marquette MI, USA) were wired in such a way that they formed three peristernal figure-8 in the body (Figure 1b). In the titanium clips method, three clips with proper dimensions for sternum (Vitalitec International Inc., Plymouth, MA, USA) were used in the first, third and fifth rib cavities, two wires were inserted into the second and fourth cavities in the form of peristernal (Figure 1c). In the titanium plate method, (MTF/Synthes CMF, West Chester, PA, USA) one of the two X-shaped plates were inserted between fourth and fifth rib cavity and the other one was inserted between the first and the second rib cavities and they were fixed with senary screws. A steel wire was applied in the form of peristernal at the third rib cavity (Figure 1d). To be fully located on sternum surface, plates were bended a little bit with application instrument. The length of the screws was determined by measuring the thickness of the sternum at the zone of application.

In the selection of these methods, the applications in the literature and the preferences made by surgeons at Atatürk University Faculty of Medicine were taken into consideration. The conventional steel wire method has been included in the study since it is the most preferred closure method due to its ease of application and low cost. The use of steel cable, titanium plate and titanium clips is increasing, even though they are much more costly than wires. These three methods were included in the scope of the study so that the studies on these materials were very few and the benefit they had to pay for their high costs could be determined.

Table 1. Compared sternum closure methods

Method	Application
Conventional wiring method	7 wires
Figure-8 with steel cables	3 steel cables + 2 wires
Titanium clips	3 titanium clips + 4 wires
Titanium plate	2 titanium plates + 3 wires

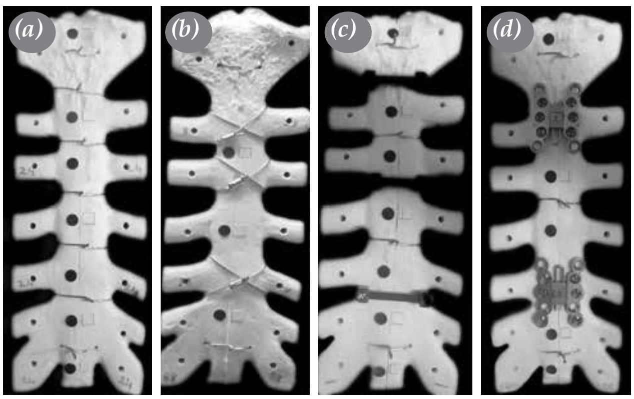

Figure 1. Compared methods in experiments; **(a)** Conventional wiring. **(b)** Figure-8 with steel cables. **(c)** Titanium clips. **(d)** Titanium plate method.

In the experiments, polyurethane sternum models (Sawbones Corporation, Pacific Research Laboratories, Vashon, WA, USA) with a density of 320 kg/m^3 were used. Various studies have been done to demonstrate the appropriateness of using these models in biomechanical experiments,[5-7] and these models have been used in many studies examining the closure methods.[3,6,8-13] The application of the cutting and closure methods of the sternum models was performed by an experienced surgeon.

The experiments were carried out by examining three different loading effects considering the current literature studies. Instead of a low and repetitive (dynamic) loading that reflects the respiratory movement, it was decided to perform a static loading in the lateral distraction load, reflecting a severe coughing effect. Rostral-caudal and anterior-posterior movements reflect the effects of forces during patient's lying on one side, supporting body with single arm or sudden movement, and in the experiments, static loadings were made while taking the physiologically sudden and short term effect of these loads into account.

Experiments were performed with the test instrument shown in Figure 2 (model 8872, Instron Corp., Norwood, MA, USA). The sternum models were fixed by screwing into the specially produced loading jaws through the holes on the seven ribs and the desired loads were applied with these jaws. For all closing methods, three tests were performed for all of the loading configurations. Also, in each different loading, two preliminary tests were performed before actual experiments. The experiments were carried out at a loading speed of 10 mm/min and the loading continued until the samples were broken (till system breaks down).

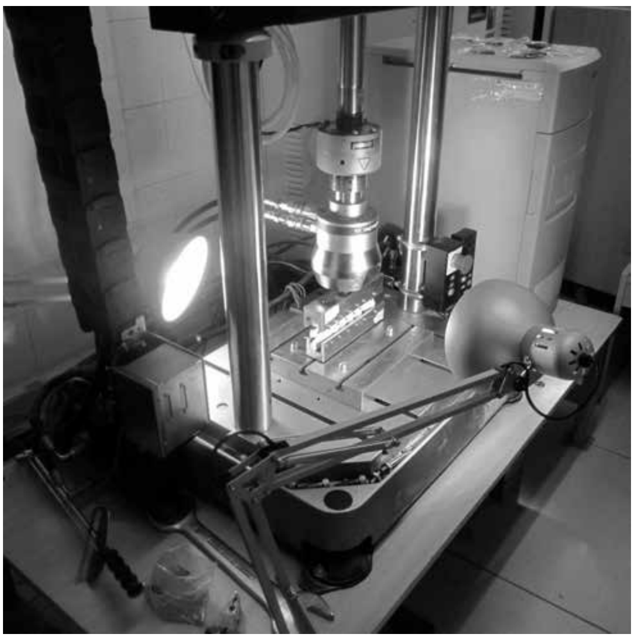

Figure 2. Realization of experiments by Instron 8872 testing apparatus.

As a result of the experiments, the load-displacement curves of the methods were generated by using the data obtained from the test instrument and the methods were compared with the help of the two parameters obtained from these curves. In the comparison of the methods, it was aimed to use the yield load value first. The portion of the load-displacement curve where the linearity it has from the beginning ends is called the yielding region. From this point, permanent (plastic) shape changes in the system start to happen and the load value corresponding to the displacement at this point is also the yield load of the system. However, it was observed that no significant yielding regions emerged in the obtained graphs. For this reason, instead of the yield load, the load value referred to as the critical displacement value for bone healing[14-16] 2 mm in different sources was called the "allowable load" and was used to compare the methods. In the second, the stiffness values of the methods were taken into account. The slope of the part between the starting point of the load-displacement curve and the yield load (allowable load) gives the stiffness value. This value is a measure of the resistance of the system to elastic elongation and the greater the stiffness the better (stable) the closure would be. The generalized load-displacement curve is shown in Figure 3. The costs of the methods, ease of implementation, and effects on the sternum models were added to the assessments made.

This study was carried out at Atatürk University Faculty of Engineering between 2014 and 2015 and conducted in accordance with the principles of the Declaration of Helsinki.

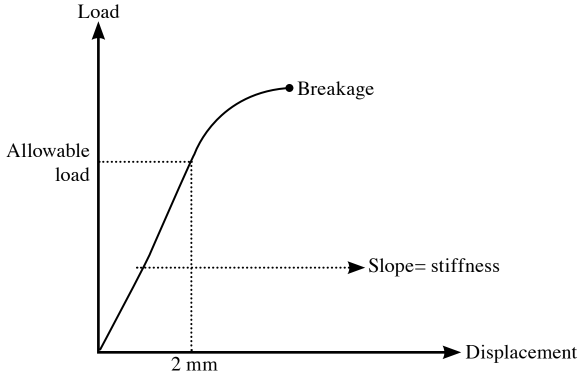

Figure 3. Generalized load-displacement curve.

Table 2. Results of experiment

Loading type	Closure method	Allowable load (N)	Stiffness (N/mm)
		Mean±SD	Mean±SD
Lateral distraction	Conventional method	1032.6±102.4	546.1±34.5
	Cable figure-8	1042.1±112.6	546.0±33.5
	Titanium clips	1184.4±109.7	616.5±41.3
	Titanium plate	1081.1±143.5	571.8±43.9
Mean±SD		1085.1±69.5	570.1±33.3
Longitudinal shear	Conventional method	579.8±30.7	383.0±19.9
	Cable figure-8	347.8±17.9	222.0±11.2
	Titanium clips	587.9±45.2	390.0±41.3
	Titanium plate	604.5±52.4	309.3±22.9
Mean±SD		530±121.9	326.1±78.4
Transverse shear	Conventional method	92.4±6.5	50.6±1.9
	Cable figure-8	89.4±17.4	44.2±5.5
	Titanium clips	206.7±17.1	120.7±7.5
	Titanium plate	166.1±11.7	93.2±0.9
Mean±SD		138.7±57.6	77.2±36.3

N: Newton; SD: Standard deviation.

Statistical analysis

One-way analysis of variance (ANOVA) was used to determine the statistical significance of the differences between the allowable loads and stiffness of the methods. As a result of the analysis, the cases where p values is less than 0.05 ($p<0.05$) were considered significant. In the determination of specific differences, multiple comparisons (post-hoc) were performed using the TUKEY test (TUKEY HSD) method. Statistical analyses were performed using the IBM SPSS 20.0 version (IBM Corp., Armonk, NY, USA) statistical analysis program.

RESULTS

The results obtained from the experiments are given collectively in Table 2 and presented in the following paragraphs.

In the lateral distraction test, the highest allowable load and stiffness values were obtained with the titanium clips method, while the titanium plate method was the second. With the conventional wiring method, which has the lowest allowable load and stiffness values, the allowable loads and stiffness of the cable figure-8 method are very close to each other. When the results were analyzed statistically, the differences between the allowable loads and stiffness of the methods were not significant ($p=0.43$ and $p=0.29$, respectively).

In the longitudinal shear test, it was seen that the method with the greatest allowable load was the titanium plate method, while the titanium clips method ranked second. The best method in terms of stiffness values was the titanium clips method while this method was followed by the conventional wiring method. The cable figure-8 method was the method with the lowest allowable load and stiffness value. As a result of the statistical analysis, it was seen that the difference in the allowable load and stiffness between the cable figure-8 method and other methods was significant ($p=1.12E-04$ and $p=1.7E-05$ respectively), the differences between the allowable loads of the other methods were insignificant ($p=0.79$). As regards with stiffness values, while the difference between the first two titanium clips and the conventional wiring method was insignificant ($p=0.69$), the difference between the two methods was found to be statistically significant ($p=1.7E-05$).

In the transverse shear test, the greatest allowable load and stiffness values were obtained by the titanium clips method, and the weakest methods were found to be the conventional wiring and cable figure-8 methods. Statistically, the allowable load and stiffness differences between the titanium clips method and the other methods were found to be significant ($p=1.4E-05$ and $p=1.3E-07$, respectively). The differences in the allowable load and stiffness between the titanium plate method and conventional wiring and cable figure-8 methods were also found to be significant ($p=4.84E-04$ and $p=4.3E-06$ respectively), the differences between the allowable load and the stiffness of the conventional wiring and cable figure-8 methods, which are the

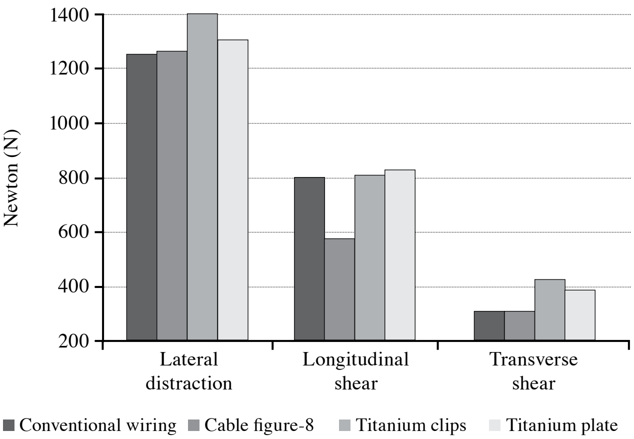

Figure 4. Comparison of allowable loads of methods.

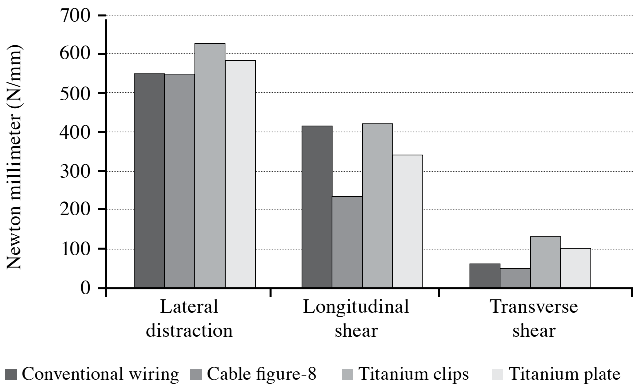

Figure 5. Comparison of stiffness of methods.

weakest methods, were not found to be significant (p=0.79 and p=0.13 respectively).

The comparison of the allowable loads of the methods is given in Figure 4. Significant differences between the values were found only between the titanium clips with transverse shear and other methods (p=1.41E-05), and with the last cut steel cable method between the other three methods. (p=1.12E-04).

The comparison of the stiffness values of the methods is shown in Figure 5. Significance among the differences was found between the titanium clips and the other methods (p=1.3E-07) in transverse shear and between the titanium clips and the conventional wiring method with two other methods (p=1.7E-05) in longitudinal shear.

When the methods were ordered according to their costs, it was determined that the most expensive method was two titanium plate methods. This method was followed by titanium clips and steel cable methods respectively. There is a huge cost difference between other methods with the conventional wiring method, which is the cheapest method. The cost of a steel cable is about 13 times the cost of one steel wire, while the cost of a titanium clip is 52 times that of steel wire. Without screws, an X-shaped titanium plate is about 70 times more expensive than steel wire. When the speed and ease of application of the methods are considered, it was determined that the fastest and easiest method is the conventional wiring method. This method was followed by titanium clips, steel cable and titanium plate methods, respectively.

DISCUSSION

In the literature, there are many experimental and clinical studies in which sternal closure methods are compared. Majority of the experimental studies have been done by examining the lateral distraction effect with static or dynamic loads.[2,6,8-13,17-22] Longitudinal and transverse shear effects were investigated in very few studies.[3,12,17,22] In this study, the effectiveness of the four different sternal closure methods was investigated under different loading conditions. The results obtained from the experiments showed that titanium clips provide a better closure than the other methods in transverse shear effect and that the conventional wiring and steel cable methods are inadequate compared to other methods in this loading case. In longitudinal clipping, the conventional wiring method with titanium clips provided better sternal closure than the other methods and it was seen that the weakest method being the steel wire method. For lateral distraction, the best allowable load and stiffness values were obtained using the titanium clips method, but none of the differences between the methods was found to be insignificant.

These results show that the titanium clips exhibit a more stable behavior and provide a better sternal closure than other comparable methods. Titanium plate and conventional wiring methods have the second and third best closing methods, respectively, and the most inadequate method seems to be steel cable figure-8 method.

It was observed that the conventional wiring method, which is the most advantageous method in terms of cost and with its ease and speed of application was inadequate in longitudinal shear even though it gave good results in lateral distraction and transverse shear. Steel wires can be applied quickly and easily with the aid of a standard porte-aiguille. Thanks to the use of a porte-aiguille, surgeons have expressed that they feel better at stretching. When the intervention to patient is necessary again, the wires can be easily

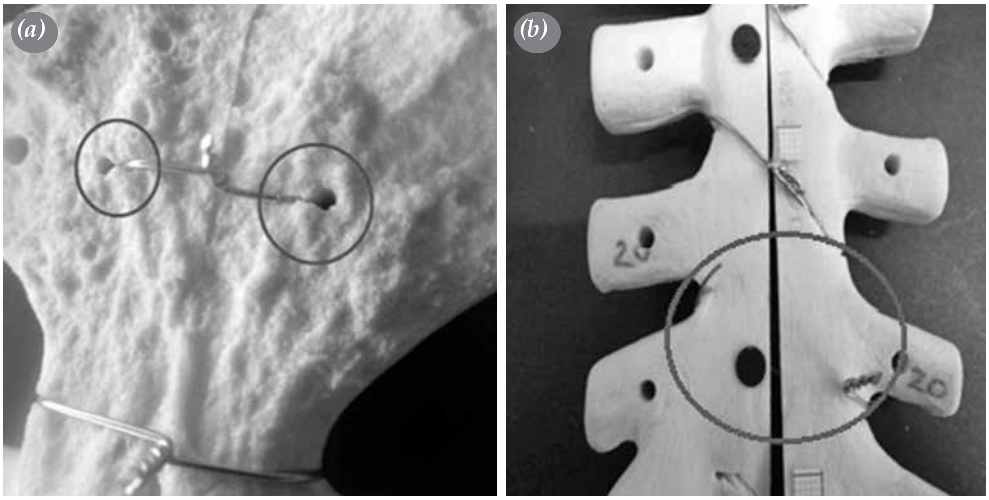

Figure 6. (a) Cutting bone by steel wires. **(b)** Breakage of steel wires.

cut and removed. Nevertheless, the most widely used (0.787 mm) wire (No. 5) in the closings easily cuts the bone with the effect of small cross-sectional areas. Before the experiments, it was seen that the wires started to cut the sternum when the wires were connected (Figure 6a). This would cause the bone to be cut more easily with the effect of forces coming to the sternum, particularly including osteoporosis, obesity, and chronic obstructive pulmonary disease (COPD). This cut-off effect, which begins in the closure of the sternum, particularly in patients with high-risk groups with osteoporosis, obesity, COPD and similar diseases, may progress very rapidly with poor bone structure and may harm bone stability and cause complications. In addition, in the total of five experiments, it was determined that the wires were broken from the node regions, and no significant opening occurred in the nodes (Figure 6b). All of the breaks in the wires occurred after the allowable load on the system was exceeded.

The mounting instrument of the cables does not allow one person to make the closure. Even though there is a display on this instrument, which is relatively difficult to use, which is showing the applied tension, it is quite difficult to ensure that sufficient tension is provided an even though the highest level on the display is exceeded, a connection, which is as rigid as closings made with wires, cannot be provided. However, due to this condition and due to the fact that the cable cross-sectional area (1.1 mm diameter) are larger than the wires, it was found that the bone cutting effect of the cables is quite low and it was found that sufficient closure is provided. In the experiments, no problems were found with the locking mechanisms of the cables and no opening or breakage occurred in the cables. In case sternum is

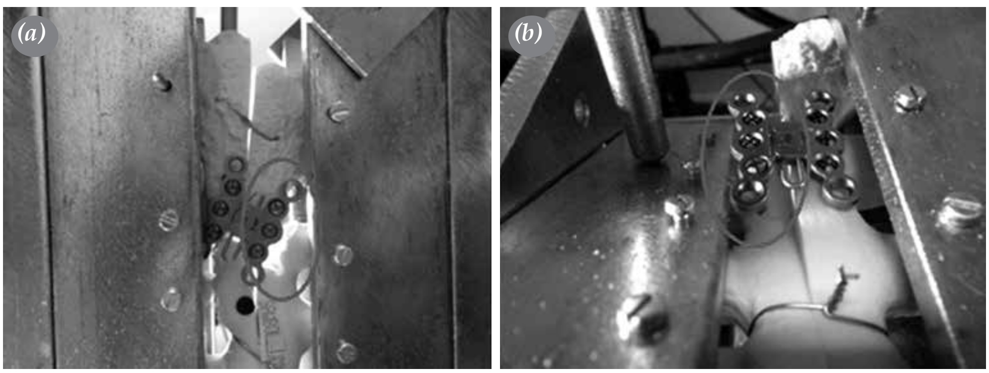

Figure 7. (a) Cut of sternum by screws at longitudinal shear effect. **(b)** Stripping of plates from sternum at transverse shear effect.

intervened again, the cables must be cut and removed and reuse would not be possible again. It is thought that the reason why the cable-figure-8 method ends up with worse results compared to the other methods is that the applied instrument used does not allow application of strain at the desired level. It is thought that the development of this instrument, which is impractical to use and extends the closure time, would allow better closure with the cables.

In the mounting of titanium clips, the sternum thickness must first be measured in the required areas to determine the correct clip size. This situation causes the prolongation of the closing time. Once the clips are inserted, they are easily fixed with the help of the clamping instrument, and cutting the excessive part of the clip requires some power. No problems were found in the locking mechanism of the clips during the experiments and no deformation of the clips was found. When the patient needs further intervention, the clips can be removed by cutting the rod of the clip or by removing the screw at the fixed end. The clip can be reused in case the screw is removed. However, since the excess of the bar would be cut in the first application, reinstalling the clip would not be easy.

In the application of plates, the width of the sternum to be used for the different plate shapes should be taken into consideration and the thickness of the sternum should be measured from the required areas when the screw sizes are determined. In order for the plates to fit properly on the surface of the sternum, it is necessary to shape the plates leaning with a special instrument and screw them carefully. Compared to other methods, this impractical process causes a considerable prolongation of the closing time. When the behavior of the plates was examined during the tests, it was seen that with the loading in the longitudinal shear experiments, the plates were forced to rotate in the direction of movement and the screws started to cut the sternum. With increase in the loading, the breaks occurred in these points (Figure 7a). In the transverse shear experiments, it was found that the screws, together with the load, started to slough off the sternum (Figure 7b). Thanks to the safety pin they have, plates, which greatly facilitates secondary intervention and is the most advantageous method in terms of reuse, remains behind other methods in terms of preference when their costs and other weaknesses are considered.

In conclusion, when experiment results and the other parameters are taken into consideration, in the cases in which the cost is not important, it's seen that closing done with three titanium clips and four steel wires is the most stable sternal closing method. It is also though that in this closing, the placement of the clips instead of the wires used in the trunk can provide a more advantageous closure due to the fact that the wires would remove the cutting effects on the bone. However, it should not be overlooked that this situation would further increase the cost.

Declaration of conflicting interests

The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

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