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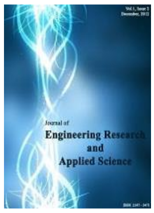

Investigation of biomechanical models for treatment of syndesmotic injury of ankle joint by finite element analysis and gray relational analysis methods

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Abstract

Ankle injuries, especially in young people and athletes are more frequent and may cause permanent disability if not treated properly. About 10% of ankle injuries consist of syndesmotic ligament injuries. Screw fixation is often used in surgical treatment. Screw fixation is made with various pieces, diameter and length screws. In this study, we aimed to determine the optimal position and diameter of the pedicle screw in ankle injuries by finite element analysis. Computed tomography (CT) images are modeled using the MIMICS (version 10.01) program as a three-dimensional (3D) solid model of the lower extremity (tibia, fibula, talus, and calcaneus) of a normal human. Cortical screw Ø 3.5 mm, Ø 4.5 mm diameter is modeled in Solidworks program. The screws are placed at three or four cortices and perpendicular to the sagittal plane to the lower extremity model. The obtained models are transferred to the ANSYS program and the loads coming to the lower extremity were applied in the normal posture position. Ti-6AL-4V titanium properties and S-N graph obtained from literature as screw material are entered into ANSYS (Version 19.0) program. The mean stress and fatigue behavior of the screw are compared. Then, the obtained values are evaluated in the Gray Relational Analysis method. As a result of finite element analysis, the maximum stresses and life span of screws of each diameter and length were calculated. It is found that the region with the least life span has the closest region of the screw where the maximum stress value is calculated. In addition, the best model is determined by Gray Relational Analysis method. The findings are similar to the position of the screw failure mentioned in the literature. This study is carried out in order to prevent postoperative complications related to the insertion of screws by surgeons. Screw that Ø4,5 mm diameter, two screws and three cortex fixation the most appropriate model. For this reason, surgeons' placement of screw counts, positions and diameters will affect the success of the operation. For this reason, it is thought that the surgeons will affect the success of the surgery by considering screw counts, position and diameter..

Keywords: Finite element model, syndesmosis, screw fixation, gray relational analysis (GRA) method.

1. Introduction

Ankle ligament injuries are the most common injuries among all sports injuries and in daily life. While the foot is in dorsal flexion, the talus is in a stable position between the two malleolus and the tibia distal joint face. On the other hand, the relationship between the tight, posterior of the talus and the malleolus is less in plantar flexion. Although talus plantar makes the flexion more active, it can cause injury by reducing stability.

Approximately 10% of ankle injuries are seen as syndesmotic injury [1]. If the syndesmotic injury is not repaired correctly, the ankle may cause loss of stability, chronic pain, and early osteoarthritis of the tibia, fibula, and talus joint surfaces [2, 3]. Many clinical and biomechanical studies have been conducted on sindesmic injury and treatment methods [4-6]. As with all orthopaedic surgeries, these methods are the most commonly used screw-fixing method. However, complications such as screw failure, syndesmosis decomposition and instability have been reported in screw use [5, 7-8].

Researches are generally composed of clinical, biomechanical and cadaveric studies, but the results may be different because their cost, time and conditions are not the same. Therefore, digital methods are becoming more widespread as they allow for unlimited repetition in more efficient and standard conditions.

In this study, finite element analysis is used to determine joint stability and stresses in the screw via changing screw diameters, number of screws and

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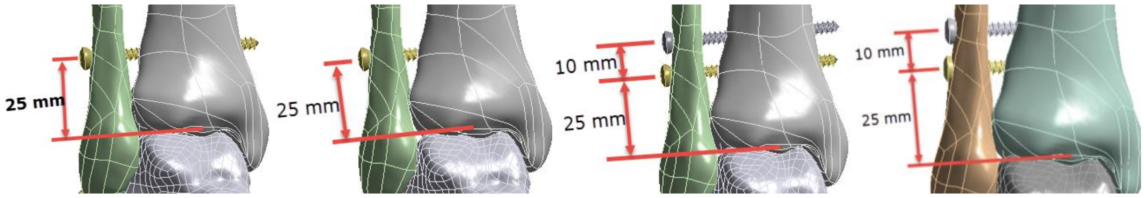
number of cortices. Thus, it is aimed to find the most stable and least stress detection method.

2. Material and method

2.1. Creating a three-dimensional model

CT images of a 35-year-old patient weighing 75 kg were performed to create three-dimensional models. The patient's lower extremity CT scan was performed with a Toshiba Aquilion CT device. The sections in DICOM (Digital Imaging and Communications in Medicine) format were sent to MIMICS 12.11 (material's Interactive Medical Image Control System/ materialise NV, Belgium) for the creation of 3D models of the lower extremity elements. Models created with MIMICS and GEOMAGIC studio program were sent to SolidWorks (Dassault Systems, USA) and the cancellous bone structures were modelled. The 3D model of the lower extremity shown in Fig. 1 was created.

In this study, cortical screws with Ø 3.5 mm and Ø 4.5 mm diameter, 45 mm and 65 mm length, commonly used in Syndesmotic injuries, were designed in 3D by the Solidworks program. The cortical screws were placed 25 mm above the joint level and parallel, as shown in Fig. 1 (a, b, c and d). In addition, they were modelled as a double with a distance of 10 mm. The screws were placed as 3 and 4 cortices and 8 different models were obtained.



a) b) c) d)

Figure 1. Ø 3.5 mm and 4.5 mm screw layouts.
a) 4 cortex single screw b) 3 cortex single screw c) 4 cortex two screws d) 3 cortex two screws

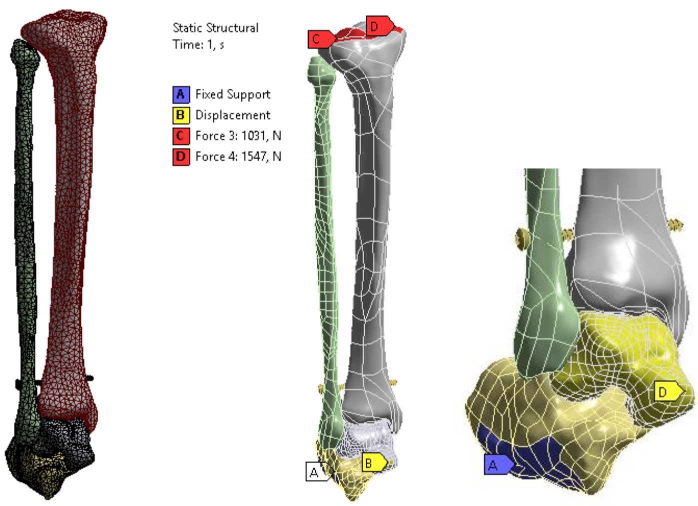
Mesh and Material Properties***;*** as shown in Fig. 2 a mesh structure was created. Ten-node tetrahedral elements were used to form the mesh of the finite elements models. The mesh size was given 5 mm in bone structures. The mesh size was given 5 mm in bone structures. The model consists of 108115 nodes and 60743 elements on average. Solid 185 and solid 285 were used as elements. The analyses were performed non-linearly.

According to the studies in the literature, material properties of cortical bone, concellous bone and cortical screw (Ti6Al4V) were selected as isotropic material as shown in Table 1 [9-11].

Tablo 1. Bone and other material properties.

	Young Modulus (E) (MPa)	Poisson Ratio (y)
Cortical Bone	17,000	0.3
Cancellous Bone	700	0.2
Titanium (Ti-6Al-4V)	106,000	0.33

Boundary and loading conditions***:*** ANSYS® (Version 15, Ansys Inc.,USA) was used to analyze the stress/load distribution, or maximum equivalent stress (MES) (von Mises stress), on screw. No separation contact types were defined between bones structure. Frictionless contact types were defined between the screw and bone structure. In addition, according to the studies, fix support was selected in the lower part of the calcaneus in the posture position as shown in Fig. 2c. As shown in Fig. 2b, 40% of the pressure force was applied to the medialine 1031 N of the upper surface of the tibia and 60% of the pressure fore was applied to lateral surface of the tibia as 1547 N force [12-15].



a b c

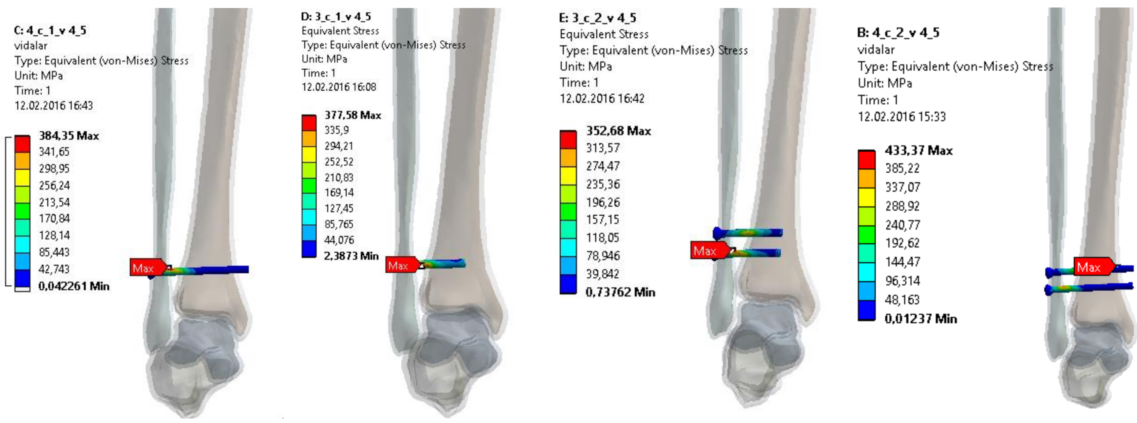
Figure 2. a) Finite element model of lower extremity b), c) Finite element loading and boundary conditions.

3. FEA analysis results

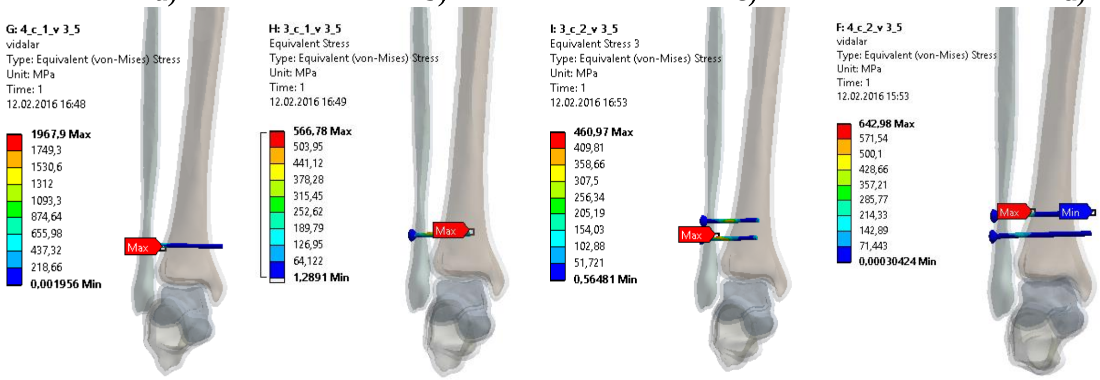
The maximum equivalent stress obtained in finite element analysis results was determined in the model with two screws parallel to the tibial joint, screws diameter of 3,5 mm and three cortices. It was seen that the highest von mises stress values in the screws occurred in the region where the screw entered the tibia. The maximum von mises stress and fatigue distributions in cortical screws are shown in Table 2. According to these results, the maximum von misses stress occurred in the fifth model and the maximum stress was 642,98MPa and the fatigue life was 3781,5 cycles. The minimum von misses stress is in the fourth model, the maximum equivalent stress in this model is 352,68MPa, and fatigue life is 9,462e + 007 cycles. The results obtained from the analyses are consistent with the experimental data. The strain distributions of Von misses Stress in the models are shown in Fig. 4.

Tablo 2. FEA analysis results.

Model No	Models	Equivalent von Mises Stress (MPa)	Lifetime (Cycle)	Distance between Fibula and Tibia (mm)
1	4 cortices ø 4,5 2 screws	433,37	2273900	4,021
2	4 cortices ø 4,5 1 screw	384,35	17452000	4,019
3	3 cortices ø 4,5 1 screw	377,58	23103000	5,1
4	3 cortices ø 4,5 2 screws	352,68	94620000	3,812
5	4 cortices ø 3,5 2 screws	642,98	3781,5	4,84
6	4 cortices ø 3,5 1 screw	613,44	3852,7	5,25
7	3 cortices ø 3,5 1 screw	566,78	27512	4,842
8	3 cortices ø 3,5 2 screws	460,97	661370	4,536



a) b) c) d)



e) f) g) h)

Figure 1. Von misses stress distributions.
a) 4 cortex, ø 4.5 single screw b) 3 cortex, ø 4.5 single screw c) 4 cortex, ø 4.5 two screws d) 3 cortex, ø 4.5 two screws e) 4 cortex, ø 3.5 single screw f) 3 cortex, ø 3.5 single screw g) 4 cortex, ø 3.5 two screws h) 4 cortex, ø 3.5 double screws

4. Determination of the best model with gray related analysis method

Considering the studies on multi-criteria decision-making methods, it is possible to find many different examples and methods. Among these methods, Gray Relational Analysis (GRA) is a method that is used more in different fields and is found to be more and more self-contained every day [16, 17, 18]. The gray theory proposes solutions for problems that do not fit any distribution, do not contain sufficient data and cannot be modeled due to uncertainty. Gray Theory was first introduced by Julong Deng in 1982. The gray theory of modelling and solving problems that cannot be solved by stochastic or fuzzy decision making methods; It is a frequently used method for inter-system analysis, model building, forecasting and decision-making problems [19, 20].

In this section, the results obtained from the FEA method for determining the best model were evaluated in the GRA method. In the evaluation phase, the factors von Mises Stress, distance between fibula-tibia and lifetime were considered. In the study, only the results obtained from the algorithm steps of the GRA method are included. For the steps and detailed information of the method, the studies of Kuo et al., (2008) and Lin and Lin (2002) can be examined.

Firstly, the minimum values are taken into account when constructing the reference series of factors the equivalent von Mises Stress and distance between fibula-tibia. The normalization process was evaluated as "lower better". In lifetime factor, "higher better" status was taken into consideration and maximum values were used in normalization. The values obtained from the normalization are given in Table 3.

Table 3. Normalization of factors.

Model No	Models	Equivalent von Mises Stress (MPa)	Lifetime (Cycle)	Distance between Fibula and Tibia (mm)
1	4 cortices ø 4,5 2 screws	0,72205	0,0239929	0,85466
2	4 cortices ø 4,5 1 screw	0,89091	0,1844104	0,85605
3	3 cortices ø 4,5 1 screw	0,91423	0,2441359	0,10431
4	3 cortices ø 4,5 2 screws	1,00000	1,0000000	1,00000
5	4 cortices ø 3,5 2 screws	0,00000	0,0000000	0,28512
6	4 cortices ø 3,5 1 screw	0,10176	0,0000008	0,00000
7	3 cortices ø 3,5 1 screw	0,26249	0,0002508	0,28373
8	3 cortices ø 3,5 2 screws	0,62697	0,0069501	0,49652
	Reference Series	1	1	1

Normalized results are subtracted from the reference series and the distance matrix required for the coefficient matrix is obtained (ξ =0,5 for the coefficient matrix calculation). The calculated coefficient matrix results for all models are presented in Table 4.

Table 4. Coefficient matrix.

Model No	Models	Equivalent von Mises Stress (MPa)	Lifetime (Cycle)	Distance between Fibula and Tibia (mm)
1	4 cortices ø 4,5 2 screws	0,64271	0,33875	0,77478
2	4 cortices ø 4,5 1 screw	0,82089	0,38006	0,77646
3	3 cortices ø 4,5 1 screw	0,85357	0,39813	0,35825
4	3 cortices ø 4,5 2 screws	1,00000	1,00000	1,00000
5	4 cortices ø 3,5 2 screws	0,33333	0,33333	0,41156
6	4 cortices ø 3,5 1 screw	0,35759	0,33333	0,33333
7	3 cortices ø 3,5 1 screw	0,40404	0,33339	0,41109
8	3 cortices ø 3,5 2 screws	0,57272	0,33488	0,49827

After calculating the coefficients of the coefficients, the gray relational degrees given in Table 5 were calculated and the GRA ranking was obtained.

Table 5. Gray relational degree and ranking.

Model No	Models	Gray Degree	Ranking by GRA
1	4 cortices ø 4,5 2 screws	0,585	3
2	4 cortices ø 4,5 1 screw	0,659	2
3	3 cortices ø 4,5 1 screw	0,537	4
4	3 cortices ø 4,5 2 screws	1,000	1
5	4 cortices ø 3,5 2 screws	0,359	7
6	4 cortices ø 3,5 1 screw	0,341	8
7	3 cortices ø 3,5 1 screw	0,383	6
8	3 cortices ø 3,5 2 screws	0,469	5

As shown in Table 5, the highest value in gray relational degrees was obtained from model 4 (3 cortices ø 4.5 2 screws).

Table 6 shows the rankings obtained from the FEA and GRA method. When Table 6 was examined, the best model in both FEA and GRA methods was "3 cortices, ø4.5, 2 screws" Accordingly, the use of 3 cortices and 2 screws of ø 4.5 in the design will make the design optimal.

Table 6. Comparison of fea and gra method results.

Model No	Models	Ranking by FEA	Ranking by GIA
1	4 cortices ø 4,5 2 screws	4	3
2	4 cortices ø 4,5 1 screw	3	2
3	3 cortices ø 4,5 1 screw	2	4
4	3 cortices ø 4,5 2 screws	1	1
5	4 cortices ø 3,5 2 screws	8	7
6	4 cortices ø 3,5 1 screw	7	8
7	3 cortices ø 3,5 1 screw	6	6
8	3 cortices ø 3,5 2 screws	5	5

5. Discussion and conclusion

The most complex link to the Sindezmoz ankle [21], since the load distribution between the tibia-fibula talus is constantly changing with movements during walking, the injury mechanisms are quite different. Ankle injuries, especially in young people and sports are seen more often increases the importance [22, 23]. An ideal anatomy of the syndesmotic injury and distal tibiafibular joint (the distance between the tibia fibula joint should be 2-3 mm.) is required [24]. The continuation of the ideal reduction during the surgical treatment is essential for the success of the treatment a decrease or increase in the distance between the tibia and the fibula may cause progressive instability, osteoarthritis and pain in the ankle [25]. Sindesmz injuries are divided into three groups, roughly light, medium and serious, and the serious group forms the group that needs surgical treatment [13].

The most common clinical and biomechanical study in syndesmotic injuries is the screw fixation method. The features of the screw, the number of cortex involvement is the main subject of study. In this study, 8 different models were created according to screw diameter, number of cortices and number of screws. As it is not possible to use the 4.5 mm diameter screw at all times due to the thin fibula and other accompanying injuries, an alternative Ø 3.5 mm screw was used. Full-fluted cortical screws were used because The Association for the Study of Internal Fixation Manual of Internal Fixation recommended full fluted cortical screw replacement instead of malleol screw [26].

In this study, it was determined that all parameters used for model design were the screw diameter parameter of the most important element. Comparing Ø 3.5 mm screw with Ø 4.5 mm screw, the lowest Equivalent von Mises Stress Ø 4.5 mm screw was obtained in all configurations. This result shows that the use of Ø 4.5 mm diameter screw will provide a more durable and strong fixation than the Ø 3.5 mm diameter screw. This result was obtained by Hansen et al., [27] shows parallelism with the results of their study. Xenos et al., [28] reported that the two screws were more stable than the single screw in the cynecrosis injury. Penera et al., [29] in their cadaver study; they reported that when two sindeesmoz screws were sent, the proximal screw had a high risk of perforating the perforating branches of the peroneal artery. Stuart and Panchbhavi [30] found that the delivery of transsindematotic screws with suprasindesmotic screws resulted in similar clinical and radiological results.

In our study, two screw submissions reduce Equivalent von Mises stress in three cortices, while four cortices do not reduce stress in three cortices. However, this is probably due to the negative effects of four cortices rather than two screws. Therefore, if the region to which be sent to screw two screws can be preferred. In our study, two screw submissions reduce Equivalent von Mises stress in three cortices, while four cortices do not reduce stress in three cortices. However, this is probably due to the negative effects of four cortices rather than two screws. Therefore, if the region to which be sent to screw two screws can be preferred. According to the results obtained from the FEA and GRA methods, the best model is the same. This result shows that the best model can be used to solve real life problems.

References

[1] Michelson, J., Solocoff, D., Waldman, B., Kendell, K., & Ahn, U. (1997). Ankle fractures. The Lauge-Hansen classification revisited. Clinical orthopaedics and related research, (345), 198-205.

[2] Hamid, N., Loeffler, B. J., Braddy, W., Kellam, J. F., Cohen, B. E., & Bosse, M. J. (2009). Outcome after fixation of ankle fractures with an injury to the syndesmosis: the effect of the syndesmosis screw. The Journal of bone and joint surgery. British volume, 91(8), 1069-1073.

[3] Porter, D. A., Jaggers, R. R., Barnes, A. F., & Rund, A. M. (2014). Optimal management of ankle syndesmosis injuries. Open access journal of sports medicine, 5, 173.

[4] Er, M. S., Verim, O., Eroglu, M., Altinel, L., Gokce, B., & Tasgetiren, S. (2015). Biomechanical evaluation of syndesmotic screw design via finite element analysis and taguchi's method. Journal of the American Podiatric Medical Association, 105(1), 14-21.

[5] Walker, L., & Willis, N. (2015). Weber C ankle fractures: a retrospective audit of screw number, size, complications, and retrieval rates. The Journal of Foot and Ankle Surgery, 54(3), 454-457.

[6] Peek, A. C., Fitzgerald, C. E., & Charalambides, C. (2014). Syndesmosis screws: how many, what diameter, where and should they be removed? A literature review. Injury, 45(8), 1262-1267.

[7] Schepers, T. (2011). To retain or remove the syndesmotic screw: a review of literature. Archives of orthopaedic and trauma surgery, 131(7), 879-883.

[8] Jordan, T. H., Talarico, R. H., & Schuberth, J. M. (2011). The radiographic fate of the syndesmosis after trans-syndesmotic screw removal in displaced ankle fractures. The Journal of Foot and Ankle Surgery, 50(4), 407-412.

[9] Özkan, A., Atmaca, H., Mutlu, İ., Çelik, T., Ugur, L., & Kisioglu, Y. (2013). Stress distribution comparisons of foot bones in patient with tibia vara: a finite element study. Acta of bioengineering and biomechanics, 15(4).

[10] Walke, W., Paszenda, Z., & Kaczmarek, M. (2008). Biomechanical analysis of tibia-double threaded screw fixation. Archives of Materials Science and Engineering, 30(1), 41-44.

[11] Gray, H. A., Taddei, F., Zavatsky, A. B., Cristofolini, L., & Gill, H. S. (2008). Experimental validation of a finite element model of a human cadaveric tibia. Journal of biomechanical engineering, 130(3), 031016.

[12] Haraguchi, N., Armiger, R. S., Myerson, M. S., Campbell, J. T., & Chao, E. Y. (2009). Prediction of three-dimensional contact stress and ligament tension in the ankle during stance determined from computational modeling. Foot & ankle international, 30(2), 177-185.

[13] Beumer, A., Van Hemert, W. L., Swierstra, B. A., Jasper, L. E., & Belkoff, S. M. (2003). A biomechanical evaluation of the tibiofibular and tibiotalar ligaments of the ankle. Foot & ankle international, 24(5), 426-429.

[14] Attarian, D. E., McCrackin, H. J., DeVito, D. P., McElhaney, J. H., & Garrett Jr, W. E. (1985). Biomechanical characteristics of human ankle ligaments. Foot & ankle, 6(2), 54-58.

[15] Stauffer, R. N., Chao, E. Y., & Brewster, R. C. (1977). Force and motion analysis of the normal, diseased, and prosthetic ankle joint. Clinical orthopaedics and related research, (127), 189-196.

[16] Murad Pepe, İ., & Ergul, E. U. (2018). Analysis of Prevent Adjacent Segment Fractures After Vertebroplasty with Variable Amount of Bone Cement by Using FEA and GRA. Journal of Biomaterials and Tissue Engineering, 8(3), 328-335.

[17] Üstünışık, N. Z. (2007). Türkiye'deki iller ve bölgeler bazında sosyo-ekonomik gelişmişlik sıralaması araştırması: gri ilişkisel analiz yöntemi ve uygulaması. Yüksek Lisans Tezi, Ankara, Gazi Üniversitesi Fen Bilimleri Enstitüsü.

[18] Kursun, B., Kurt, U., Guvercin, S., Okten, K., Akgul, S., & Yildiz, A. (2016). An application for the failure mode and effects analysis integrated with the grey relational analysis. Trakya University Journal of Engineering Sciences, 17(2), 35-44.

[19] Kuo, Y., Yang, T., & Huang, G. W. (2008). The use of grey relational analysis in solving multiple attribute decision-making problems. Computers & industrial engineering, 55(1), 80-93.

[20] Lin, J. L., & Lin, C. L. (2002). The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics. International Journal of Machine Tools and Manufacture, 42(2), 237-244.

[21] Browner, B. D., Jupiter, J. B., Levine, A. M., Trafton, P. G., & Krettek, C. (2009). Skeletal trauma: basic science, management, and reconstruction. Philadelphia: Saunders.

[22] Press, C. M., Gupta, A., & Hutchinson, M. R. (2009). Management of ankle syndesmosis injuries in the athlete. Current sports medicine reports, 8(5), 228-233.

[23] Williams, G. N., Jones, M. H., & Amendola, A. (2007). Syndesmotic ankle sprains in athletes. The American journal of sports medicine, 35(7), 1197-1207.

[24] Harper, M. C., & Keller, T. S. (1989). A radiographic evaluation of the tibiofibular syndesmosis. Foot & ankle, 10(3), 156-160.

[25] Sagi, H. C., Shah, A. R., & Sanders, R. W. (2012). The functional consequence of syndesmotic joint malreduction at a minimum 2-year follow-up. Journal of orthopaedic trauma, 26(7), 439-443.

[26] Müller, M. E., Allgöwer, M., Allgower, M., Schneider, R., & Willenegger, H. (1991). Manual of internal fixation: techniques recommended by the AO-ASIF group. Springer Science & Business Media.

[27] Hansen, M., Le, L., Wertheimer, S., Meyer, E., & Haut, R. (2006). Syndesmosis fixation: analysis of shear stress via axial load on 3.5-mm and 4.5-mm quadricortical syndesmotic screws. The Journal of foot and ankle surgery, 45(2), 65-69.

[28] Xenos, J. S., Hopkinson, W. J., Mulligan, M. E., Olson, E. J., & Popovic, N. A. (1995). The tibiofibular syndesmosis. Evaluation of the ligamentous structures, methods of fixation, and radiographic assessment. JBJS, 77(6), 847-856.

[29] Penera, K., Manji, K., Wedel, M., Shofler, D., & Labovitz, J. (2014). Ankle syndesmotic fixation using two screws: risk of injury to the perforating branch of the peroneal artery. The Journal of Foot and Ankle Surgery, 53(5), 534-538.

[30] Stuart, K., & Panchbhavi, V. K. (2011). The fate of syndesmotic screws. Foot & ankle international, 32(5), 519-525.