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A two-dimensional wrist model for carpal instability and force transmission

Karpal instabilite ve yük aktarımının incelenmesinde iki boyutlu bir el bileği modeli

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Objective

Distribution of internal forces among the carpal bones and ligaments, and contribution of the supporting ligaments to the integrity of the wrist was investigated.

Patients and methods

Wrist radiograph of a healthy volunteer was used to develop the model. The SAP 2000 computer program was used to model the bones, cartilage and ligaments. Initially, a total of 143 Newton of compression load was applied from the metacarpals and internal force distribution across the wrist joint was recorded. Then, internal forces on the ligaments were measured after a total of 143 N of tension load was applied along the longitudinal axes of the metacarpals. The intact and ligaments-sectioned wrists were concomitantly evaluated.

Results

81% of the loads were dissipated through the radius. Lunotriquetral ligament was loaded in tension with the highest values in the intact wrist. After removing of the ligaments from the system alone or as pairs, the internal force was distributed among the ligaments in various patterns.

Discussion

To our knowledge, this is the first study to analyze the internal force distribution along the carpal ligaments. Findings of the present study may contribute to the better understanding of the biomechanical pathoanatomy of carpal instability.

Key words: Carpal ligaments, force transmission, instability, wrist, finite element model.

Amaç

Bu çalışmanın amacı dışardan uygulanan kuvvetlerle el-bilek kemikleri ve bağlar arasında iç kuvvetlerin dağılımını ve bu bağların el bilek bütünlüğündeki katkısını ortaya koymaktır .

Hastalar ve yöntem

Sağlıklı bir gönüllüden elde edilen el bileği radiografileri bilgisayarda SAP 2000 programı kullanılarak kemikler, kıkırdak ve bağ modellendi. İlk aşamada toplam 143 Newton kompresyon yükü metakarpallere uygulandı ve el bileği ekleminde oluşan iç kuvvet dağılımı kayıt edildi. Daha sonra hem sağlam el bileğinde, hem de bağlar kesildikten sonra oluşan iç kuvvetler toplam 143 N germe yükü metakarpallerin uzun ekseni boyunca uygulandıktan sonra kayıt edildi.

Bulgular

Kompresyon çalışması önceki çalışmalarla uyumlu idi. Uygulanan kuvvetin %81'i radius boyunca dağıldı. Gerinim çalışmasında sağlam el bileğinde en yüksek gerinim yüklenmesi lunotrikuetral bağda görüldü. Sistemden bağlar tek ya da çift olarak uzaklaştırıldığında iç kuvvetlerin bağlarda farklı biçimlerde dağıldığı görüldü.

Çıkarımlar

Bilgilerimize göre bu çalışma karpal bağlar arasında iç kuvvet dağılımını değerlendiren ilk araştırmadır. Bu bilgiler el bileği instabilitesinin biyomekanik patoanatomisini anlamaya katkı sağlayacaktır.

Anahtar sözcükler: Karpal bağlar, kuvvet aktarımı, instabilite, iki-boyutlu model, sonlu eleman.

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The human wrist is a complex joint of small bones and ligaments that form a mobile, yet stable arrangement. Stability of the wrist is provided by the anatomic design of the individual carpal bones and by the ligamentous interconnections that control movement of one bone on another. Carpal instability is defined as inability to bear physiological loads with an associated loss of normal carpal alignment. Wrist instability results from a disruption of the ligamentous support between the individual carpal bones (intrinsic ligaments) and between the radius and the carpus (extrinsic ligaments). The misalignment may appear after a single traumatic event or may be secondary to chronic attenuation of supporting ligaments. Once the normal soft tissue constraints are lost, the carpal bones assume a pathologic orientation based on the remaining ligamentous forces.

Although several studies regarding carpal instability have been reported following the article of Linscheid et al. in 1972,[1] there still exists a great deal of confusion. Linscheid accepted it as malalignment of carpal bones while others developed concept of dynamic vs. static instability and carpal dysfunction. It is generally accepted that the disruption of a single ligament may not result in carpal instability; thus initiates a progressive instability pattern.[2-5] However, careful review of the literature reveals no information on the distribution of the internal forces carried by other ligaments after sectioning of a single ligament.

The major source of information on carpal instability has come from surgical exploration studies,[3.4] evaluation of a cadaver wrist loaded to failure[3] or selective ligament sectioning.[2] However in vitro and cadaver studies have certain limitations that only a single or a group of ligaments can be evaluated in one specimen.

Understanding the exact contribution of the supporting ligaments to the functional integrity of the wrist is crucial for the diagnosis and treatment of carpal instabilities. In order to quantify internal forces on other ligaments when a ligament was sectioned, we conducted a two-dimensional finite element study. Additionally, force transmission across the carpal joints and separation between the bones after ligament sectioning, which are assumed to be the underlying reasons of carpal instability, were investigated. We believe that this wrist model will overcome certain limitations of cadaver studies.

MATERIALS AND METHODS

Anteroposterior wrist radiograph of a 24 years of old healthy male was used to create the model. Borders of the bones were transferred to a paper divided into squares with 1:1 scale. Then a finite element mesh was produced using the SAP 2000 computer software.[6] The SAP 2000 software is a multipurpose engineering program for designing structures by integrated finite element analysis. In the present study, triangular, rectangular and quadrilateral elements of the program were used.

The model consisted of the distal 100 mm of the radius and the ulna, and the five metacarpals and the six carpal bones including, the scaphoid, the lunate, the capitatum, the hamate and the triquetrum. The trapezium and the trapezoideum were handled as a single bone and the psiform was excluded. The radius and the ulna were assumed to be immobile rigid bodies. The elastic modulus of the bones was taken as 20GPa and the Poisson ratio was taken as 0.3.[7] Cartilage was incorporated into the external borders of the bones as quadrilateral elements with a 7MPa elastic modulus and a 0.3 Poisson ratio.

Seventeen ligaments were constructed for this wrist joint model (Table 1).

Table 1. Carpal ligaments modelled in the study.

Superficial palmar ligaments	Deep palmar ligaments	Dorsal ligaments
1. Radioscaphoid (RS)	7. Short radiolunate (SRL)	16. Radiotriquetral (RT)
2. Radiocapitate (RC)	8. Ulnolunate (UL)	17. Triquetroscaphotrapezoid (TST)
3. Long radiolunate (LRL)	9. Ulnotriquetral (UT)	
4. Ulnocapitate (UC)	10. Scapholunate (SL)	
5. Scaphocapitate (SC)	11. Lunotriquetral (LT)	
6. Transverse carpal (TC)	12. Triquetrohamatocapitate (THC)	
	13. Scaphotrapezial (ST)	
	14. Transverse interosseous radial (TIR)	
	15. Transverse interosseous ulnar (TIU)	

The stiffnesses of the ligaments were obtained from a previous study.[8] After the model was completed (Figure 1), the study was performed at two stages. At the first stage, external compression load was applied along the longitudinal axis of the five metacarpals. Load distribution at the metacarpals was obtained from previous studies.[8,9] According to those studies the thumb, the index, the long, the ring and the small bones received 22.5 N, 33.0 N, 42.2 N, 25.6 N and 19.7 N forces, respectively. These loads are in order of those that would be experienced in vivo while grasping a 1 Kg (10N) force.[8]

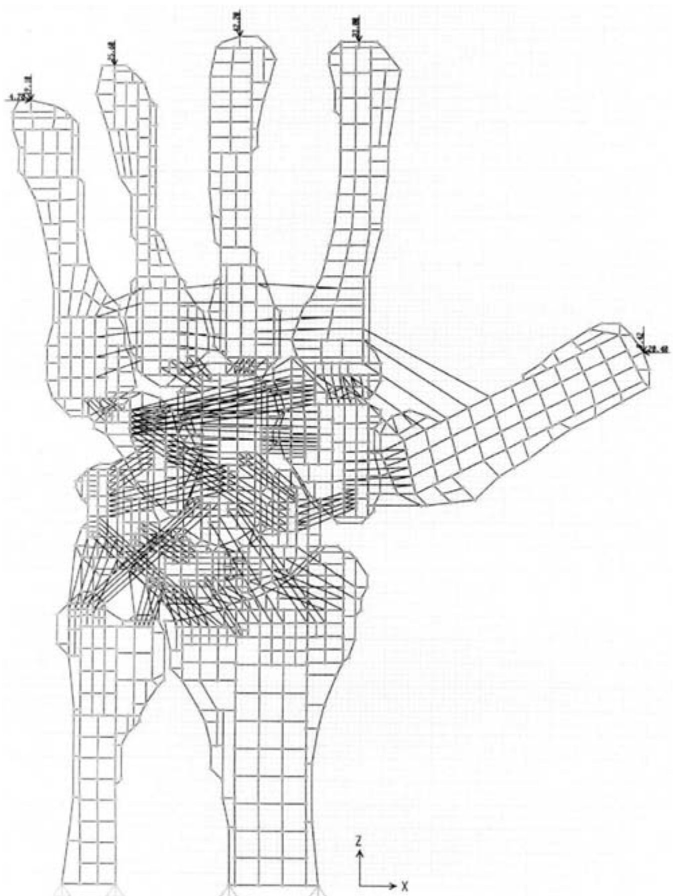

Figure 1. Final appearance of the construction

In the second stage of the study, tension loads were applied along the longitudinal axes of the metacarpals with the same magnitude of load was used in the first stage of the study. Than, the loads carried by each ligament was recorded. The ligaments were individually removed from the system sequentially and the forces on the remaining ligaments were recorded. Additionally the ligaments were removed in pairs.Finally, a scaphoid-lunate separation and a scaphoid-trapezial separation were modeled after removal of all ligaments.

RESULTS

In the compression study, 81% of the total force dissipated through the radius (50 % through the radioscaphoid and 31% through the radiolunate joint) and 19% through the ulna (13% through the ulnolunate and 6% through the ulnotriquetral joint). In the midcarpal joint, the scaphotrapezial joint transmitted more loads (35%) followed by the triquetrohamate, lunocapitate and the scaphocapitate joints with 23%, 21% and 12% of the loads, respectively. Comparative results with previous reports are displayed in Table 2.

The loads carried by each ligament under 143 N of tension force are displayed in Figure 2. The loads of the LT, the RC, the ulnocapitate (UC) and the SL ligaments were greater than the others. While the tension on the SC and the short radiolunate (SRL) ligaments were considerably low, no tension was detected on the radiotriquetral (RT) ligament (Figure 2).

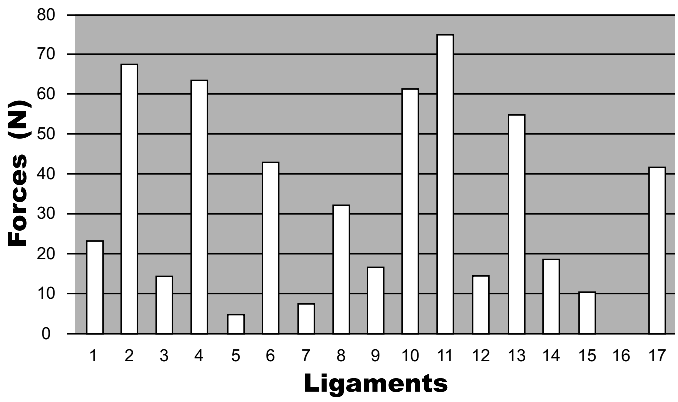

Figure 2. Loads carried by the ligaments at 143 N of tension. Numbers represent the ligaments given in Table 1.

When a superficial palmar ligament was removed from the system, the loads on the deep palmar ligaments increased more than the others. However, when the RC ligament was removed, the SC ligament, which is another superficial ligament, tensioned more than the others. When a deep palmar ligament was removed from the system, again the highest increase was noted in another deep palmar ligament; except the SRL and the radial interosseous transverse (TIR) ligament: Their removal displayed more loads in the palmar ligaments. Although removal of the dorsal ligaments presented an increase in the tension of the others, that increase was not as much as that observed at the removal of both the superficial and the deep palmar ligaments. When the ligaments were removed in pairs, the increase in tension on the other intact ligaments was higher than that observed at the removal of a single ligament. Tension on the TIR ligament increased 12.4 folds when the SL and the RC ligaments were removed. Similarly, the removal of the RC and the LRL ligaments, and the removal of the LT and the ST ligaments, resulted in about ten folds increase in the SRL and the TIR ligaments, respectively (Table 3).

Removal of the SL ligament resulted in 4.7 mm separation of the scaphoid and the lunate bones. However, there was no significant change when the

SL ligament was removed along with the LRL, the LT, the THC and the TST ligaments (Figure 3). When the RC and the SL ligaments were removed together, the separation increased by approximately two times (Figure 3). When the ST ligament was removed from the system, the separation between the scaphoid and the trapezium was 3.5 mm. Removal of the SC ligament additionally did not increase the separation but decreased it 0.2 mm. However, when the RC and the ST ligaments were removed together, separation increased more than two folds.

DISCUSSION

The concept of carpal instability has evolved considerably by previous anatomical,[5.10.11] kinematical[7.12.13] and clinical[1.14] studies. However, there still exists controversy, even in the definition of carpal instability[15] or carpal ligaments.[5.11] Initially, the term 'instability' was considered to be synonymous with 'malalignment. However, there are several potential flaws when one applies the results of an in vitro kinematic analysis to the in vivo situation. A potential disadvantage of most in vitro methods is the transducers or markers that are used which interfere with ligament and tendon function. Implementing these markers often requires exposure that damages important anatomical structures.[16]

After the completion of the model, force transmission across the carpal joints were measured in neutral position which is regarded as the standard position of the wrist joint[17] and the results were comparable with the previous reports (Table 2). To our opinion, this model can be used in basic research concerning the force transmission and in selecting appropriate procedures among the several forms of limited carpal fusions or joint leveling procedures used to treat Kienböck's disease, in individual basis.

Table 2. Force transmission ratio (%) through the wrist joint.

Joints	Present study	Horii et al. [4]	Iwasaki et al. [5]	Genda and Horii [3]	Manal et al. [11]
Radiocarpal	81	78	83	88	73
Ulnocarpal	19	22	17	12	27
Scaphotrapezial	35	31	33	28	-
Scaphocapitate	12	19	34	26	-
Lunocapitate	21	29	17	29	-
Triquetrohamate	23	21	16	17	-

In the compression study, 81% of the total force transmitted through the radius (50% through the radioscaphoid and 31% through the radiolunate joints). Similar results were reported by Iwasaki et al. (83%),[20] Horii et al. (78%)[8] and by others.[3,11] This may indicate that this wrist model is sound.

To our knowledge, there appears no study in the literature assessing the effects of tension forces on carpal ligaments. In the present study, when a 143 N tension force was applied to the model, the internal forces generated on the LT, the RC, the UC and the SL ligaments were more than the others (Figure 2). These results present the importance of these ligaments on the stability of the wrist joint. Although the role of the LT, the RC and the SL ligaments have been previously reported,[2-5. 18.19] as far as we know, this is the first study to reveal the importance of the UC ligament with quantitative results. Tension forces on the SC and the SRL ligaments were considerably low and no tension was detected on the RT ligament. These ligaments probably have function other than resisting to the tension forces. Ligament function is still an unsolved issue and compensation mechanisms are thought to mask clear correlations between the lesion and instability.[20] However, no data clarifying these mechanisms were reported. Table 3 displays the tension on the remaining ligaments after sectioning of a single ligament. When a ligament was removed from the system, the tension on the deep palmar ligaments increased more than the others (Table 3). Probably, the main compensating mechanism is on the deep palmar ligaments, but with some exceptions; i.e. the SC ligament seems to compensate the RC ligament (Table 3). On the other hand, increase on the other ligaments may be interpreted such as that these ligaments are at more risk. This is in accordance with the concept of progressive instability.[2.3.20]

In the final part of the study, separation after sectioning of the SL and the ST ligaments were analyzed (Figures 3 and 4). In both situations, additional sectioning of the RC ligament increased the separation by about two folds, revealing the importance of the RC ligament in the scapholunate and the scaphotrap "eziotrapezoidal instabilities.

Previous in vitro and cadaver studies have had certain limitations; that only one or a group of ligaments can be evaluated in a single specimen.[21] There were some limitations of the present study. In this study, a single X-ray of a male patient was used to create the model. This approach, however, was in line with previous other studies.[22,23]

Understanding the pathomechanics of carpal instability is important in the diagnosis and the treatment of patients. The data presented in this study seems to contribute to our common knowledge on carpal instability. Moreover, this model may be used in the detection of the injured ligaments of a specific patient by sequentially removing the ligaments from the system until the patient's condition can be simulated.

Table 3. Loads carried by the ligaments when a ligament or a pair of ligaments were removed from the system.

R/I	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1	-	1,44	1,31	1,03	0,6	1,01	1,79	0,22	0,91	0,64	0,93	0,93	0,91	2,21	1,05	0,41	0,15
2	1	2,23	-	3,72	1,52	4,33	0,72	-8,21	0,67	-0,16	1,22	1,99	2,32	1,22	-6,00	-4,40	0,93	0,44
3	1	0,94	1,07	-	0,98	0,58	1,04	3,86	0,89	0,94	0,91	0,81	0,86	0,99	1,46	0,90	0,85	0,87
4	1	0,62	1,32	0,41	-	2,75	1,18	2,57	1,38	3,28	1,21	0,93	-1,89	1,16	2,13	-1,10	1,86	0,57
5	1	1,93	0,99	1,41	0,99	-	1,04	2,36	0,79	0,31	0,98	0,97	0,61	1,04	1,28	1,10	0,99	1,20
6	-1	1,00	0,78	1,69	1,04	1,17	-	2,43	0,60	0,31	1,02	0,87	0,71	1,09	-0,95	-3,45	0,98	0,63
7	1	2,02	0,98	1,69	1,00	0,83	1,02	-	0,81	0,38	1,00	1,01	0,86	1,00	0,54	1,00	1,22	0,81
8	1	1,32	0,96	2,07	1,06	0,67	1,01	6,21	-	0,47	0,88	1,20	1,00	1,16	0,77	2,00	1,27	0,92
9	1	2,00	0,95	0,93	1,23	0,25	0,99	2,36	0,83	-	0,98	1,01	1,79	0,99	0,90	0,80	0,95	0,92
10	1	1,30	1,35	1,03	1,25	0,33	1,22	0,04	-0,08	0,16	-	0,47	-0,25	0,49	3,21	8,50	0,20	0,96
11	1	0,11	1,24	-1,27	0,99	-0,33	0,94	0,57	1,41	0,72	1,02	-	-0,38	0,77	2,59	3,85	0,06	1,56
12	-1	1,00	1,02	1,52	0,95	0,75	1,01	2,29	0,83	1,22	0,98	0,98	-	0,99	0,56	1,10	1,04	1,11
13	1	1,15	1,34	0,76	1,29	1,08	0,58	-0,21	-0,08	0,72	0,36	0,34	-0,14	-	2,59	4,65	0,47	0,39
14	1	2,11	0,97	1,66	1,03	1,00	0,94	2,43	0,60	0,34	1,01	0,89	0,68	0,14	-	0,55	1,00	1,05
15	1	1,57	1,01	1,45	0,98	1,00	1,13	0,93	0,81	0,97	0,99	0,83	0,89	1,01	0,62	-	1,00	0,79
16	-1	1,04	0,96	-0,41	1,30	0,42	0,95	1,14	1,43	-0,41	0,76	0,36	1,86	-0,13	1,41	1,95	-	0,88
17	1	0,96	1,04	0,76	1,05	1,17	0,64	2,21	0,60	0,19	0,93	1,00	-0,32	1,20	-0,10	-0,65	0,94	-
10+2	1	4,89	-	5,48	1,86	1,67	0,02	0,93	-1,08	1,72	-	1,26	1,57	0,46	-0,38	12,35	-0,42	1,82
10+3	1	1,38	1,33	-	1,23	-0,83	0,70	1,07	0,05	0,66	-	0,09	-	0,49	1,33	8,40	0,26	0,86
10+11	1	1,43	1,34	-0,00	1,24	-0,83	0,69	0,007	0,001	0,69	-	-	0,29	0,49	2,56	8,30	0,28	1,01
10+12	1	1,26	1,33	0,86	1,32	-0,50	1,24	0,14	0,06	0,38	-	0,20	-	0,83	1,67	8,45	0,27	1,05
10+17	1	-1,38	1,38	0,79	1,26	0,33	0,37	-0,43	0,03	0,47	-	0,42	0,54	0,70	0,92	6,85	0,31	-
2+11	1	1,98	-	0,03	1,91	1,58	0,36	0,21	2,13	-1,69	1,28	-	-0,07	0,80	-0,18	-6,50	-1,59	2,02
2+3	1	2,38	-	-	1,59	3,33	0,81	10,06	1,00	0,6	0,78	0,67	1,64	1,24	-0,38	-0,70	0,27	1,77
2+17	1	2,12	-	0,53	1,59	5,17	0,23	3,79	0,59	-0,44	1,45	1,98	1,39	0,86	-3,79	-2,40	0,85	-
2+12	1	2,29	-	3,76	1,42	4,00	0,49	3,64	0,68	1,91	1,24	1,97	-	1,19	-1,00	0,60	1,06	1,54
3+11	1	-0,01	1,29	-	-1,03	-0,33	0,86	-3,21	1,41	1,22	0,47	-	-0,18	0,72	2,44	4,80	0,11	0,87
3+17	1	1,91	1,22	-	1,03	1,17	0,67	3,43	0,84	1,16	0,92	0,45	0,32	1,19	0,46	-0,80	0,81	-
3+12	1	2,15	0,89	-	0,55	0,42	1,04	3,79	0,90	1,16	0,97	0,80	-	0,94	0,44	1,00	0,88	1,07
11+12	1	0,11	1,31	-1,31	0,93	-0,17	0,95	0,57	1,43	0,59	0,58	-	-	0,95	1,54	3,80	-0,02	0,99
11+17	1	1,74	1,35	-1,24	1,01	1,00	0,61	0,50	1,35	0,56	0,11	-	0,36	0,79	2,05	2,00	0,04	-
12+17	1	1,89	1,04	1,21	1,03	1,17	1,36	2,21	0,95	0,72	0,93	-	-	1,19	-0,13	-0,65	0,94	-

R: Ligaments removed, I: Intact ligaments. The numbers of the ligaments are according to Table 1. Values less than 1.00 represent compression

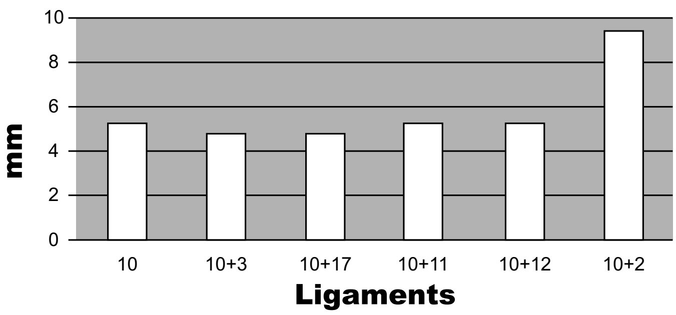

Figure 3. Separation of the scapholunate interval. Numbers represent the ligaments given in Table 1.

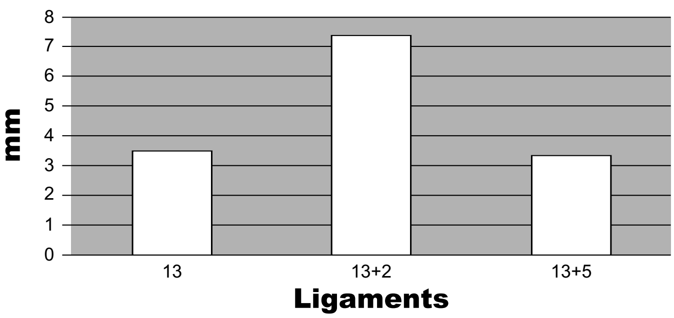

Figure 4. Separation of the scaphotrapezoid interval. Numbers represent the ligaments given in Table 1.

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