MODIFICATIONS TO THE MECHANICAL BEHAVIOR OF THE WRIST AFTER FRACTURE OF THE SCAPHOID. MODELING BY FINITE ELEMENT ANALYSIS

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Although based on their long-term clinical evolution there appeared to be no doubt that fractures of the scaphoid modify the mechanical behavior of the carpus, the mechanisms of these modifications have not yet been investigated. This study based on finite element analysis provides insight into the sequence behind the onset of arthritis of the wrist, highlighting the existence of pressure peaks at the nonunion and at the midcarpal interface (scaphoid-capitate and lunate-capitate). This evidence explains the clinical evolution of nonunions of the scaphoid.
Our study indirectly demonstrates the role played by the scaphoid within the wrist as a force transmission column.
The use of finite element analysis for the modeling of simple or complex osteoarticular systems may prove to be a highly useful tool for the understanding of these mechanisms.

Keywords : biomechanics ; scaphoid ; fracture.
Mots clés : biomécanique ; scaphoïde ; fracture.

INTRODUCTION

The scaphoid is the most frequently fractured carpal bone. The diagnosis and treatment of such fractures are problematic. In fact, many fractures are not detected and progress to nonunion, as shown by a multicentric study carried out by Alnot, who reported that 70% of nonunions were secondary to undiagnosed fractures (1). The treatment of fractures of the scaphoid yields very diverging results as healing rates ranging from 3% to 97 % have been reported (3, 4, 6, 12).

Nonunion of the scaphoid develops with progressive arthritic lesions reflecting a disruption of the mechanical behavior of the wrist (2, 4, 7, 8, 9, 10, 14).

MATERIALS AND METHODS

We set up a model of the wrist in two dimensions using the finite element software ***ALGOR*** (Algor Inc., 150 Beta Drive, Pittsburg, U.S.A.). This type of software enables modeling complex structures while defining mechanical properties for each of the components of the model. The principle consists in “meshing” the object under review in finite elements. These elements are triangular or quadrangular in shape for the flat parts, but they may also be bars, and they provide a means of reproducing the geometry to be studied. The unknown factors of the problem are the displacements of the vertices and extremities of such elements.

We traced the bone geometry based on an anterior-posterior xray of a healthy pronated wrist. The trapezium and the trapezoid were represented by one single block of bone given, on the one hand, the difficulties in

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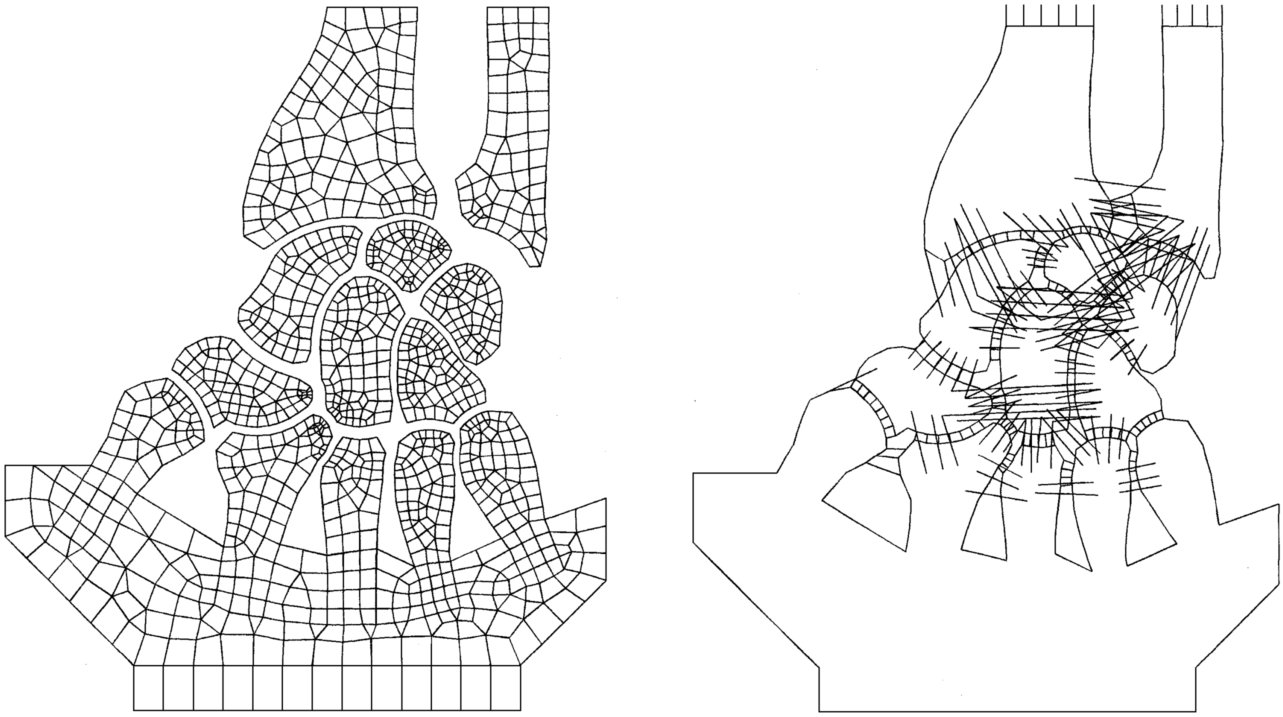

Fig. 1. — Finite element modeling of the wrist in two dimensions

distinguishing between the two bone contours on xrays and, on the other hand, the relative lack of mobility between the two bones. The pisiform was not represented in our model as its role is not significant in the transmission of loads.

We stopped the modeling of the two bones of the forearm a few centimeters above the radiocarpal interface, as only the transmission of loads at the wrist joint was of interest to us. A load of 100 newtons (N) was applied by means of a "block" joining the five metacarpals, thus simulating the experimental conditions of the study of Trumble *et al.* (13).

The different skeletal elements were "meshed" by the automatic mesh generator of the software, which led to the definition of 1053 nodes (fig. 1).

The peripheral nodes served as insertion points for the non-linear elements that model the articular interfaces, and the ligament insertions were situated at the level of interior nodes.

The behavior of the ligaments and of the cartilage is of the non-linear type, as the ligaments can only undergo traction and the cartilage compression.

We adopted an elasticity module (Young's modulus) of 50 megaPascal (MPa) for the ligaments, 15 MPa for the cartilaginous interfaces and 18 000 MPa for the bone.

Different situations were modeled : the intact wrist, a distal fracture of the scaphoid below the scaphoradial interface (type V), and four fractures at the level of the scaphoradial interface more and more proximal on the scaphoid (fig. 2). These different fractures correspond to Schernberg types I to V (11).

The different models were all subjected to the same load, and the pressures were measured at the articular interfaces.

To ensure the coherence of the model, we checked that the 100 N of load applied to the edge of the block joining the metacarpals were found again at the level of both radius and ulna.

RESULTS

We measured the pressures (N/mm^2) at the radioscaphoid, radiolunate, lunocapitate and scaphocapitate articular interfaces.

The radioscaphoid interface is represented by seven linking elements, and the radiolunate

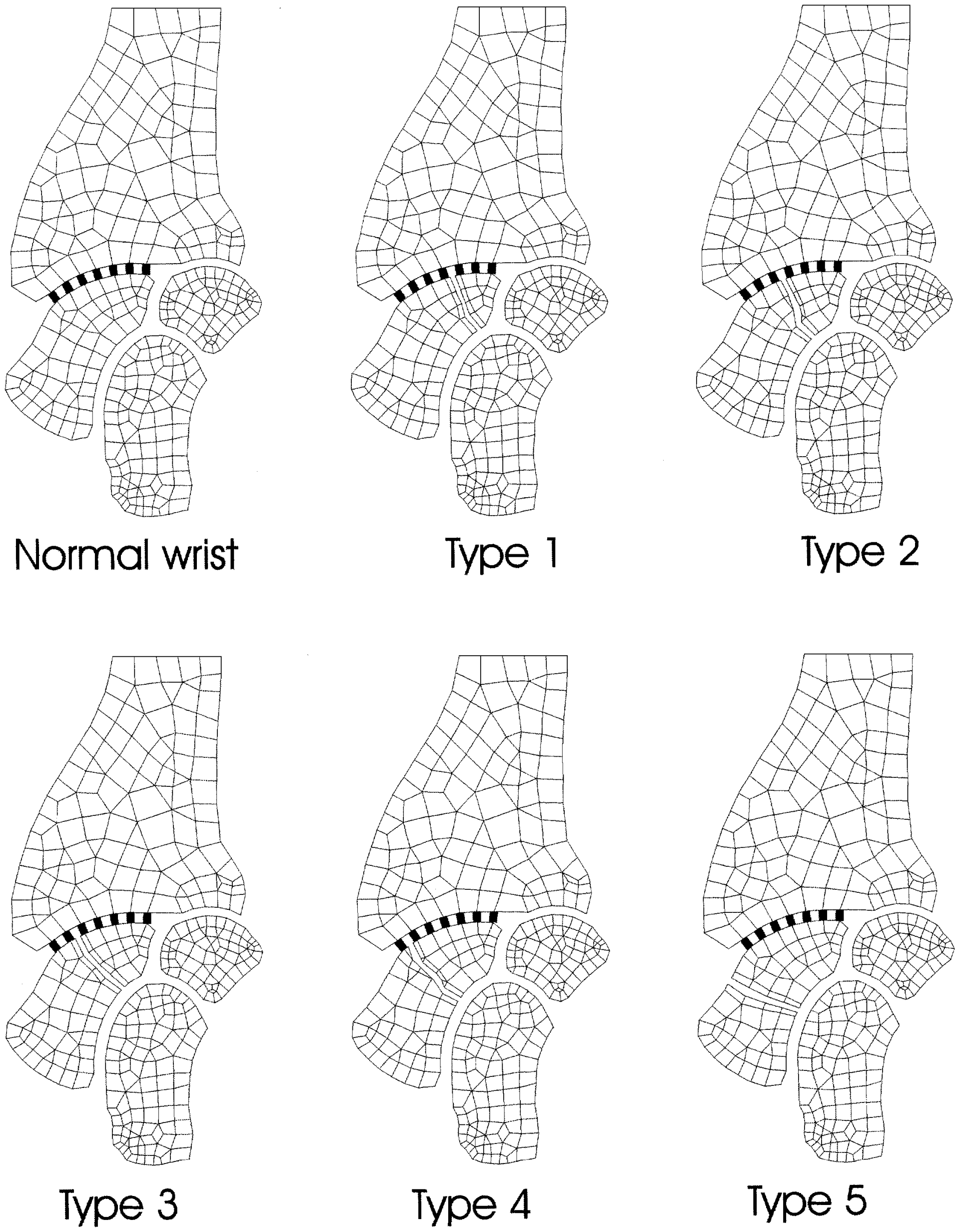

Fig. 2. — Modeling of the intact wrist and 5 types of scaphoid fracture

interface is represented by six linking elements of which the mechanical characteristics are those of the cartilage (Young's modulus : 15 MPa).

The results at the radioscaphoid interface are given in table I. In the situation of the healthy wrist, the pressures range from 0.442 to 0.5513 N/mm^2. In the case of a fracture type V, the increases in pressure are slight, reaching 0.577 N/mm^2 (i.e. 105% of the maximum pressure in the healthy wrist) at the level of the most compressed element. In contrast, there is a gradual decrease in pressures in the most proximal elements.

In the case of fractures involving the radio-scaphoid interface, it can be seen that maximum pressure (p max) is measured at the level of the most proximal element on the distal scaphoid

Table I. — Pressure in N/mm^2 at the level of the different elements of the radioscaphoid interface

	element 1	element 2	element 3	element 4	element 5	element 6	element 7
intact wrist	0.422	0.4828	0.5148	0.5369	0.5493	0.5513	0.5431
type 5	0.577	0.519	0.453	0.379	0.3	0.214	0.125
type 4	0.99	0.534	0.46	0.38	0.29	0.2	0.099
type 3	0.729	0.91	0.49	0.4	0.3	0.19	0.08
type 2	0.515	0.64	0.76	0.58	0.39	0.19	0
type 1	0.463	0.58	0.686	0.78	0.415	0.246	0.069

Table II. — Maximum pressure for the different types of fracture in the radioscaphoid, scaphocapitate and lunocapitate interfaces

Type of fracture	P max	%	P max	%	P max	%
intact wrist	0.5513		1.34		0.5674	
type 5	0.5773	105%	1.762	131%	0.74	130%
type 4	0.9867	179%	1.674	125%	0.74	130%
type 3	0.9089	165%	1.616	121%	0.744	131%
type 2	0.7606	138%	1.506	112%	0.733	129%
type 1	0.7803	142%	1.402	105%	0.692	122%

fragment. The increase in pressure is highest for the type IV fracture as the pressure reaches 179% of p max measured on the healthy wrist. The more proximal the fracture, the smaller the increase in pressure, but the pressure nonetheless reaches 138% for the type II fracture.

Table II shows the values of p max and the percentage in relation to the p max recorded for the healthy wrist in the radioscaphoid, scaphocapitate and lunocapitate interfaces. We observe here that the increase in p max is greatest at the radioscaphoid level, followed by the lunocapitate level and finally in the scaphocapitate interface, although the difference between these two interfaces is not significant. The increase in pressure is most important at the level of the most distal fracture involving the scaphoradial interface.

Study of the radiolunate and radioscaphoid articular interfaces above the level of the fracture shows a modification in the stress distribution at the radioscaphoid and radiolunate level (table III). In the situation of the healthy wrist, 70.7% of the loads pass through the radioscaphoid interface and 29.3% through the radiolunate interface. In the case of a fracture of the scaphoid, the proportion of forces that pass through the radiolunate interface increases, and increases even more as the fracture is more distal. For type V fractures, the balance is 52.9% at the radiolunate level versus 47.0% at the radioscaphoid level.

Table III. — Transmission of loads from the scaphoid and the lunate to the radius for the different types of fracture

type of fracture	radioscaphoid interface	radiolunate interface
Normal wrist	70.7%	29.3%
type 5	47.1%	52.9%
type 4	50.4%	49.6%
type 3	53.9%	46.1%
type 2	56.1%	43.9%
type 1	60.9%	39.1%

DISCUSSION

There is a general consensus in the literature (2, 4, 7, 8, 9, 10, 14) that untreated nonunions of the scaphoid will result into the gradual onset of arthritis (fig. 3).

Vender *et al.* (14), in a study involving the radiological analysis of 64 nonunions of the scaphoid, showed a predictable sequence towards

Fig. 3. — Nonunion of the scaphoid 17 years after the fracture. Arthritis of the radioscaphoid, scaphocapitate and lunocapitate interfaces.

the appearance of arthritis in the wrist joint. The radiolunate and radioscaphoid interfaces above the fracture are always spared. The arthritis always appears first at the radioscaphoid interface at the level of the nonunion. The next part to be affected is the scaphocapitate interface above the level of the fracture followed by the lunocapitate space. On this point there appears to be a discordance with our results as we observe a slightly larger increase in the p max between the capitate and the lunate than between the capitate and the proximal pole of the scaphoid. It is likely that the dorsal rocking motion of the lunate (DISI) which is observed in nonunion of the scaphoid explains this difference. Indeed, under these conditions, the height of the lunate interposed between the capitate and the radius is reduced, and the lunate is partly spared the thrust of the capitate ; consequently the pressure on the proximal fragment of the scaphoid increases. It is probably this mechanism that protects the radio-lunate interface from the development of arthritis in nonunions of the scaphoid.

In support to this hypothesis, Vender *et al.* noted that there was midcarpal arthritis in 91% of wrists with a DISI compared with 40% in the absence of DISI. This was confirmed by the findings of Bonnevialle *et al.* (2), since in their series of 477 nonunions only 29% of nonunions that did not present any DISI deformation exhibited arthritis. It should be noted that the overall rate of arthritis in the latter study was 37%, which is much less than in the series of Vender *et al.*, but unfortunately in the Bonnevialle study the nonunions were not studied according to the duration of their development. This discrepancy in the rate of osteoarthritis observed in the Bonneviale study could be explained by a shorter follow-up.

Our study indirectly demonstrates the role of the scaphoid in the transmission of forces from the hand to the forearm as the proportion of forces which is transmitted through the lunate increases as the interruption of the scaphoid column becomes more distal.

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SAMENVATTING

P. LEDOUX, D. LAMBLIN, R. TARGOWSKI. Mechanische veranderingen in de pols tegenvolge van een scaphoid fractuur. Modelvorming door middel van eindige elementen.

De frakturen van het scaphoid zijn een frequente traumatische pathologie, met soms een moeilijke diagnose, en waarvan de behandeling gepaard gaat met een relatief belangrijk mislukkingspercentage.
De evolutie van de pseudarthrosen gaat in de zin van een progressief optreden van een radio-scaphoidale en eventueel medio-carpaal arthrose.
Bij ons weten werden de mecanismen van deze arthrotische evolutie niet bestudeerd. Het doel van deze studie is een model op te stellen van verschillende typen van frakturen van het scaphoid door de methode van de eindige elementen en door de wijzigingen te bestuderen van het mecanisch gedrag van de pols ten gevolge van deze frakturen. Wij noteren het bestaan van belastingspieken ter hoogte van de proximale extremiteit van het distale fragment, evenals een wijziging van de verspreiding van de radio-scaphoidale en radio-lunaire inspanningen alsook op het niveau van de medio-carpale gewrichtsspleet. Deze vastellingen laten toe de klinische evolutie van de pseudarthrosen van het scaphoid uit te leggen.

RÉSUMÉ

P. LEDOUX, D. LAMBLIN, R. TARGOWSKI. Modification du comportement mécanique du poignet après fracture du scaphoïde. Modélisation par la méthode des éléments finis.

Les fractures du scaphoïde sont des lésions traumatiques fréquentes, de diagnostic parfois difficile, et dont le traitement est grevé d'un taux d'échec relativement important. L'évolution des pseudarthroses se fait vers l'apparition progressive d'une arthrose radio-scaphoïdienne et parfois aussi médio-carpienne. A notre connaissance, les mécanismes de cette évolution arthrosique n'ont pas été étudiés. Le propos de ce travail est de modéliser différents types de fracture du scaphoïde par la méthode des éléments finis et d'étudier les modifications de comportement mécanique du poignet suite à ces fractures. Nous notons l'existence de pics de contraintes au niveau de l'extrémité proximale du fragment distal, ainsi qu'une modification de la répartition des contraintes au niveau des interlignes radio-scaphoïdien et radio-lunaire ainsi qu'au niveau de l'interligne médio-carpien. Ces constatations permettent d'expliquer l'évolution clinique des pseudarthroses du scaphoïde.