Force transmission through the juvenile idiopathic arthritic wrist: a novel approach using a sliding rigid body spring model

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Abstract

Force transmission across the wrist during a grasping maneuver of the hand was simulated for three children with juvenile idiopathic arthritis (JIA) and for one healthy age-matched child. Joint reaction forces were estimated using a series of springs between articulating bones. This method (i.e., rigid body spring modeling) has proven useful for examining loading profiles for normally aligned wrists. A novel method (i.e., sliding rigid body spring modeling) designed specifically for studying joint reaction forces of the malaligned JIA wrist is presented in this paper. Loading profiles across the wrist for the unimpaired child were similar using both spring modeling methods. However, the traditional fixed-end method failed to converge to a solution for one of the JIA subjects indicating the sliding model may be more suitable for investigating loading profiles of the malaligned wrist. The results of this study suggest that a larger proportion of force is transferred through the ulno-carpal joint of the JIA wrist than for healthy subjects, with a less than normal proportion of force transferred through the radio-carpal joint. In addition, the ulnar directed forces along the shear axis defined in this study were greater for all three JIA children compared to values for the healthy child. These observations are what were hypothesized for an individual with JIA of the wrist.

Keywords: JRA; JCA; Kinetics; Carpal bones; Springs; Modeling

1. Introduction

The wrist is a complex biomechanical structure comprised of eight carpal bones, the proximal metacarpals, the distal ulna and the distal radius. The bones of the wrist are interconnected with intrinsic and extrinsic ligaments forming at least 18 articulating surfaces. The wrist is an important structure without which strength and dexterity of the hand would be greatly compromised.

Juvenile idiopathic arthritis (JIA) is a heterogeneous group of systemic inflammatory diseases affecting children below the age of sixteen years. JIA, previously recognized as JRA or juvenile chronic arthritis (JCA) is characterized by a chronic inflammation of one or more of the joints and is a leading cause of childhood disability (Cassidy and Petty, 1990). JIA can lead to pathological deformation of the hand and wrist severely affecting activities of daily living. In a review of 414 patients diagnosed with JIA, Chaplin et al. (1969) noted wrist involvement in 487 of 828 wrists (59%). Findlay and colleagues (1983) reported a similar value (63%). Granberry and Mangum (1980) reported that 77% of children with wrist involvement experienced partial or total loss of wrist flexion and/or extension. Without the ability to flex or extend the wrist, even simple activities may prove problematic and impact the quality of life. Furthermore, JIA can have long-term degenerative consequences. Eighty percent of children evaluated twenty years or more after the onset of severe JIA had signs of joint abnormality (Nalebuff et al., 1972).

Ulnar translation of the carpus is a pathomechanical characteristic of the arthritic wrist (Linscheid, 1971; Pirela-Cruz et al., 1993; Nieuwenhuis et al., 1999). In extreme cases, the term “glissement carpien”, French for sliding carpus, has been used when describing carpal bones that appear to slide off the end of the forearm (Chaplin et al., 1969). Gonzalez and colleagues (1996) summarized a mechanism for ulnar translation of the wrist...
arthritic wrist proposed by Linscheid (1986) as follows: “the development of carpal ulnar displacement is believed to be the result of a loss of ligamentous constraint in combination with the compressive forces of the muscles acting across the wrist and the inclination angle of the radius”. For example, the distal radius slopes towards the ulna at an average angle of 24° (Schuind et al., 1992), although Linscheid (1971, 1986) reports a lesser angle of 14°. Irrespective of the exact degree of inclination, an axial load applied to the carpus will tend to cause the bones to displace in an ulnar direction if not opposed by restraining ligaments (Taleisnik, 1988). Compressive axial loading of the carpus is common because most hand activities produce an axial compressive force across the wrist (Cooney et al., 1989). Ligamentous laxity caused by joint effusion and muscle malfunction due to spasm and altered mechanics are typical of patients suffering from RA (Swezey, 1971; Findley et al., 1983). The amount of carpal ulnar translation may be related to the extent of this laxity. The palmar radiolunate and radiocapitate ligaments are purported to be primary restraints of carpal ulnar displacement (Schuind et al., 1985; Linscheid, 1986). Different findings based on in-vitro sectioning of these ligaments have been reported by Viegas et al. (1995). In their study, an axial load of 143N was applied through the metacarpals with the wrist positioned in several combinations of flexion/extension and ulnar/radial deviation. Significant carpal ulnar translation was not evident when the radiolunate and radiocapitate ligaments were sectioned. They only found notable ulnar displacement of the wrist if compromise of ligaments was severe and global. Although the role of the palmar ligaments opposing ulnar translation of the carpus may be debated, children with JIA often present with carpal ulnar deviations.

Ulnar translation of the carpus may be related to changes in ligamentous integrity, the frontal plane inclination of the radius, changes in the shape of the carpal bones due to the diseases process and ostensibly affected by shortening of the ulna rendering any possible buttressing effect of the triangular fibrocartilage complex ineffective. In addition, it is hypothesized that larger than normal ulnar directed forces arise in the JIA wrist when loaded axially, causing the carpus to displace in an ulnar direction. To examine this hypothesis requires a method of estimating joint reaction forces across the many articulations of the wrist. Ideally this method should be sensitive to the aforementioned variables that may be related to carpal ulnar translation. One such method is rigid body spring modeling (RBSM). RBSM has been used to study joint contact forces at the wrist (Garcia-Elias et al., 1989; Horri et al., 1990; Schuind et al., 1995; Iwasaki et al., 1998). Cartilage and ligaments are represented by compressive and tensile springs, respectively. Compressive springs are “fixed” to bones on either side of an articulating surface, while tensile springs follow the lines-of-action of the ligaments. Elements (i.e., bones) of the RBSM displace when subject to an external load and settle into static equilibrium after a period of oscillation. Joint reaction and ligamentous forces can then be estimated knowing the deformation in the springs. Compressive springs are eliminated from the analysis if they are stretched beyond their resting length, and tensile springs eliminated if they are compressed. These situations (i.e., eliminating springs) can occur when a bone is subject to off-center loading causing it to rotate about its center of mass (COM). Off-center loading happens when the applied load does not pass through, or in close proximity to the COM of the bone. External loads are applied along the metacarpals of the RBSM to simulate axial loading of the carpus typical of in-vivo hand movements. The applied forces along the metacarpals are not constrained to pass through the COM of the distal carpal bones, nor are the reaction forces constrained between the distal and proximal rows. This is potentially problematic when creating spring models of the JIA wrist since pathological malalignment of the carpal bones will result in greater off-center loading than would otherwise be expected in a healthy wrist, causing the model to collapse if a sufficient number of springs fail.

A novel approach of RBSM is presented in this paper. This approach differs from the previously described fixed-end model by allowing the distal end of each compressive spring to slide along the border of the distal bone contour. The sliding end of each compressive spring searches for the shortest distance from its fixed end on the proximal bone to a point on the distal bone border. As a result, fewer compressive springs are expected to be stretched and consequently fail due to off-center loading. The sliding RBSM may prove more robust to off-center loading than the fixed-end model and therefore more suitable for studying joint reaction forces and loading profiles in the JIA wrist.

The first purpose of this study was to assess the efficacy of the sliding RBSM by comparing results obtained using the sliding method and a traditional fixed-end approach. It was hypothesized the sliding RBSM would be more robust to off-center loading and therefore a more suitable analysis tool with which to study joint kinetics of the pathologically malaligned arthritic wrist. The second purpose of this study was to estimate compressive and ulnar directed forces during a simulated grasping maneuver for three JIA subjects and a healthy child.

A larger proportion of force transferred through the ulno-carpal joints was expected for the JIA subjects than for the healthy child. That is, as the carpus migrates towards the ulna, the radius becomes partially unloaded and the load across the ulno-carpal joints increases. Greater carpal translation and therefore greater loading...
of the ulno-carpal joints was expected for the JIA subjects. For the same reason, it was hypothesized that the proportion of force transmitted through the radiocarpal joints would be less for the JIA subjects. In addition, ulnar directed forces for the JIA subjects were expected to be greater than for the healthy child. These hypotheses were based on the geometry of the wrists and did not take into account the documented laxity of the ligaments which is known to occur in JIA (Swezey, 1971; Findley et al., 1983). The ligaments of the JIA wrists were modeled the same way as the ligaments for the healthy wrist because the mechanical properties of the ligamentously lax JIA wrist are not known. Limitations of this study preclude inferring greater carpal ulnar translations are the consequence of greater ulnar directed forces, however, the geometries of the subject specific models differed sufficiently to expect greater ulnar directed forces in response to axial loading of the metacarpals.

2. Materials and methods

Four subjects participated in this study (3 JIA & 1 age-matched unimpaired child). Postero-anterior radiographs of the wrist were acquired for each subject. Subjects were instructed to align the third metacarpal and longitudinal axis of the forearm to the best of their ability. Image modeling (IMOD) software (University of Colorado, Boulder, CO.) was used to digitize the scanned radiographs and define 2D bone contours for the following structures: the proximal ends of the metacarpals (1–5), 6 carpal bones, distal radius (R) and distal ulna (U). The six carpal bones included the scaphoid (S), lunate (L), triquetrum (T), hamate (H), capitate (C), trapezium and trapezoid (TT). The trapezium and the trapezoid were treated as a single body in the current model because they could not be distinguished from one other in the postero-anterior radiographs. The pisiform was not included in the analysis because it is a sesamoid bone and does not contribute appreciably to force transmission across the wrist. An axis representing the distal articulating surface of the radius was superimposed on the digitized bone contours. This axis, based on work by Shapiro (1970) was used to define the shear direction of the proximal carpal bones on the distal forearm. Examples of digitized bone contours and the shear axis are illustrated in Fig. 1.

The mass of each bone was estimated from the area of the digitized bone contour and published values for bone density (Cowin, 1989). Moments of inertia were estimated using the formula for a rectangle since most bones were assumed rectangular in shape. This 2D rectangular representation was based on the generalization that carpal bones can be represented schematically as a cube (Berger and Garcia-Elias, 1991). The digitized 2D bone contours of the RBSM will be referred to as bones throughout this paper.

Compressive linear springs representing cartilage and subchondral bone were distributed along joint contact lines at intervals of 0.7–1.0 mm. Spring stiffness was set at 17 N/mm per spring, resulting in an average linear stiffness across each articulating surface of approximately 200 N/mm. Sixteen tensile springs representing intrinsic and extrinsic ligaments were included in each RBSM. End points for each tensile spring (i.e., ligaments) were approximated based on illustrations from previously published studies (Cooney et al., 1989; Berger and Garcia-Elias, 1991; Schuind et al., 1995). Ligament specific spring values based on data published by Schuind and Cooney (1985), and Hori and colleagues (1990) were used in the analysis.

The locations of the compressive and tensile spring end-points relative to the bones to which they were attached remained fixed and therefore the term fixed-end RBSM was used to describe the traditional RBSM method. Spring constants for each of the tensile springs...
were similar to values reported in the literature (Nowak, 1991; Schuind et al., 1995). Over 300 compressive and 16
tensile springs were included in each RBSM.

Metacarpals 1–5 were loaded axially to simulate
forces required to grasp a 1 kg load and prevent it from
slipping through the hand. The following loads were
applied through the COM of the metacarpals following
the longitudinal axis of each bone: 21.5 N thumb, 34.3 N
index, 42.2 N long, 25.9 N ring and 18.1 N small. The
total force applied load along the metacarpals was
142N, identical to the loading protocol used by Schuind
and colleagues (1995). Metacarpals and carpal bones
were free to displace under the applied load while the
radius and the ulna remained fixed. Spring forces
proportional to changes in spring length were calculated
as per Eq (1):
\[ F = -k(L_0 - L_1) \]

where \( k \) is the spring constant and \( L_0 \) and \( L_1 \) are the
spring resting and final lengths, respectively.

The total compressive force between articulating
bones was defined as the summation of individual
spring forces projected onto a body link vector. The
body link vector originated at the COM of the distal
bone forming the articulating pair and was directed
towards the COM of the proximal bone as illustrated in
Fig. 2. Reaction forces between carpal bones in the same
row were calculated in a similar manner with the more
ulnar positioned bone treated as proximal. Projection of
spring forces onto the body link vector minimizes the
affect of shear on compressive force estimates. Resultant
compressive forces across the radio-carpal and ulno-
carpal joints were calculated in the inertial reference
system and projected onto the shear axis to estimate the
magnitude of the ulnar directed force.

Although our goal was to study the loaded carpus
under static conditions, we used a dynamic analysis in
which the metacarpals were loaded using a step function
and then examined the steady state solution. SD/
FAST™ (Symbolic Dynamics Inc.) software was used to
calculate relative displacements of the bones when
subject to an externally applied load. A Runge–Kutta
4th order explicit integration formula with a time step of
0.01 s was used to integrate the reaction forces and
determine relative bone displacements. Simulations were
carried out for 20 s (i.e., 2000 time steps) after which two
conditions were evaluated to assess if the RBSM was in
a quasi-static state suitable for force analysis. Condition:
(1) kinetic energy of the entire spring system below 5%
of the peak value during the 20 s simulation; condition,
(2) linear and angular velocities of each bone less than
10\(^{-4}\) m/s and 10\(^{-3}\) rad/s, respectively. The RBSM was
considered quasi-static and suitable for analysis if both
these conditions were satisfied. Failure to satisfy either
condition implied the model collapsed or was on the
verge of collapsing at the end of the simulation.

The only difference between the fixed-end model and
the sliding RBSM was the distal end of each compres-
sive spring was free to move along the distal bone
contour searching for the shortest distance relative to
the fixed end of the spring attached to the proximal
bone. Each bone contour was defined from several
hundreds digitized points. If an extensive search of all
possible points were conducted at every time step, the
20 s simulation would have required over 3000 h to run
on a 300 MHz Silicon Graphic Graphic Octane™ workstation.
Therefore, rather than searching every possible point on
the distal contour for the shortest distance, the
algorithm tested four points on either side of the current
distal point for the shortest distance. The assumption
was that relative movement between articulating bones
at each time step would be less than the distance from
the current distal point to four points on either side of
the current point. The shortest distance algorithm was
called by every compressive spring and executed at every
time step during the simulation. Material properties,
bone masses and moments of inertia, as well as all other
modeling parameters and quasi-static stop criteria were
identical to values used for the fixed-end RBSM.

3. Results

All forces are reported as a percentage of the total
applied load (142 N). For the purposes of this study,
only results for the compressive springs of the most
proximal carpal bones will be reported. Results for both
models are presented in Table 1. Notice the fixed-end
spring model did not converge (DNC) for subject 2. This indicates the fixed-end model did not satisfy the stop criteria for static equilibrium. In contrast, the sliding RBSM method did converge to a near static state for subject 2 and was suitable for analysis. The proportion of force transmitted through the radio-scaphoid joint of the JIA wrists was less than the normal wrist. This was true using both the fixed-end and sliding models.

Table 1
Percentage of total applied load transmitted between the proximal carpal bones and the radius and ulna. NB: DNC indicates the model did not converge during the simulation and that static analysis of the spring forces could not be performed. Results for the one age-matched unimpaired subject are reported in the gray column. Means and standard deviations for the JIA subjects are reported under the column heading JIA (SD). Individual JIA subject data are reported in the last three columns of the table.

<table>
<thead>
<tr>
<th>Articulation</th>
<th>Unimpaired</th>
<th>JIA (SD)</th>
<th>JIA (1)</th>
<th>JIA (2)</th>
<th>JIA (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>radio-scaphoid</td>
<td>54.8</td>
<td>37.7 (3.4)</td>
<td>40.1</td>
<td>DNC</td>
<td>35.3</td>
</tr>
<tr>
<td>radio-lunate</td>
<td>25.4</td>
<td>35.8 (5.2)</td>
<td>32.1</td>
<td>DNC</td>
<td>39.5</td>
</tr>
<tr>
<td>ulno-lunate</td>
<td>12.7</td>
<td>14.9 (1.4)</td>
<td>15.9</td>
<td>DNC</td>
<td>13.9</td>
</tr>
<tr>
<td>ulno-triquetral</td>
<td>7.1</td>
<td>11.7 (0.4)</td>
<td>11.9</td>
<td>DNC</td>
<td>11.4</td>
</tr>
<tr>
<td>capitate-lunate</td>
<td>16.3</td>
<td>27.7 (4.1)</td>
<td>24.8</td>
<td>DNC</td>
<td>30.7</td>
</tr>
<tr>
<td>radio-scaphoid</td>
<td>49.0</td>
<td>41.5 (5.1)</td>
<td>47.3</td>
<td>39.0</td>
<td>38.1</td>
</tr>
<tr>
<td>radio-lunate</td>
<td>23.8</td>
<td>22.7 (6.5)</td>
<td>16.9</td>
<td>29.6</td>
<td>21.5</td>
</tr>
<tr>
<td>ulno-lunate</td>
<td>17.4</td>
<td>17.9 (2.8)</td>
<td>21.1</td>
<td>16.0</td>
<td>16.4</td>
</tr>
<tr>
<td>ulno-triquetral</td>
<td>9.8</td>
<td>18.0 (5.2)</td>
<td>14.7</td>
<td>15.4</td>
<td>24.0</td>
</tr>
<tr>
<td>capitate-lunate</td>
<td>16.2</td>
<td>29.0 (9.9)</td>
<td>24.0</td>
<td>22.6</td>
<td>40.3</td>
</tr>
</tbody>
</table>
Conversely, reaction forces between the ulno-triquetral joint were larger for the JIA wrists as might be expected with carpal ulnar displacement. In addition, joint reaction forces between the capitate and ulnate were greater for the JIA wrists than for the healthy child. Average joint reaction forces for the fixed-end and sliding models are illustrated in Fig. 3. Fig. 3 is a graphical summary of the data reported under the column JIA Average in Table 1.

A graphical representation of the starting and ending positions of the bones for the sliding RBSM (1 unimpaired, 3 JIA) are illustrated in Fig. 4. For illustration purposes, the linear and angular displacements of the bones were scaled by a factor of 10. In general, displacement of the carpal bones was primarily vertical in direction for the normal wrist, while a greater ulnar directed component was noted for the JIA subjects. The JIA subjects also exhibited a greater ulnar directed force along the shear axis than the magnitude of the force for the healthy child (Table 2).

4. Discussion

The purposes of this study were twofold. The first purpose was to assess the efficacy of a novel RBSM method for estimating joint reaction forces at the wrist. The sliding RBSM has been described in abstract form (Geesaman and Buchanan, 1998) and is expanded upon in this paper. It was hypothesized the sliding RBSM would be less prone to collapse than the fixed-end model because fewer compressive springs were expected to fail as a result of off-center loading of the carpal bones. Off-center loading was expected, especially for the JIA subjects because of pathological malalignment characteristic of the disease (Nieuwenhuis et al., 2001). The outcome that all four sliding RBSM (3 JIA and 1 unimpaired) converged to a quasi-static state suitable for force analysis agreed with our a priori hypothesis. Further supporting the robustness of the sliding RBSM was that it converged to a solution for JIA subject 2, but the fixed-end RBSM did not converge for the same subject. JIA subject 2 had the most severely malaligned wrist of the 3 JIA subjects and radiological signs of “glissement carpien” were evident (Fig. 4).

Convergence of the method should not be the sole criteria for evaluating the efficacy of the sliding model. That is, if the method converges to a quasi-static solution but does not yield physiologically meaningful results it is not a useful tool with which to study force transmission at the wrist. The physiological feasibility of the results using the sliding RBSM can be inferred from the data for the one healthy child. Force transmission profiles for the unimpaired subject using both modeling

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**Fig. 3.** Proportion of applied force transmitted through radio-ulnar-carpal joints of the JIA wrists. Results for the two-fixed end RBSM are based on data for two subjects, while the results for the sliding model are based on data for all three JIA wrists. The applied load was 142 N.

**Fig. 4.** Graphical illustration of the starting and ending positions of the carpal bones for the sliding RBSM. Starting positions are defined by black lines; red lines are used to display final positions. NB: the linear displacements were scaled by a factor of 10 to facilitate visual comparisons.

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**Table 2**

Resultant force along the shear axis and directed towards the ulna expressed as a percentage of the total applied load (142 N). The values are based on results using the sliding RBSM with data for the one age-matched unimpaired subject reported in the top row.

<table>
<thead>
<tr>
<th>RBSM</th>
<th>Subject</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding</td>
<td>Unimpaired</td>
<td>42.7</td>
</tr>
<tr>
<td></td>
<td>JIA(1)</td>
<td>62.7</td>
</tr>
<tr>
<td></td>
<td>JIA(2)</td>
<td>87.3</td>
</tr>
<tr>
<td></td>
<td>JIA(3)</td>
<td>47.1</td>
</tr>
<tr>
<td></td>
<td>JIA average (SD)</td>
<td>65.7 (20.3)</td>
</tr>
</tbody>
</table>
methods were similar to data for normal adults performing a similar simulated grasping maneuver (Schuind et al., 1995; Iwasaki et al., 1998). The percentage of force transmitted through the normal radio-scaphoid joint in the present study was approximately 53% (average of fixed-end and sliding models) while the proportion of force for healthy adults was 55% in the previously cited studies. Likewise, forces at the other radio-ulno-carpal joints were also similar. Data for the one healthy subject were not intended to characterize loading patterns of the intact wrist in general, but rather included as a reference against which data for the JIA subjects could be compared and the physiological feasibility of the sliding results assessed against the fixed-end RBSM. The proportion of force transmitted through the radio-ulno-carpal joints for the healthy child was similar to values reported for healthy adult subjects, suggesting the sliding RBSM results were physiologically meaningful and the method appropriate for estimating joint kinetics of the wrist. Similarity of the results using the fixed-end and sliding RBSM methods for the normal wrist were not surprising because carpal motion was predominantly vertical in direction with little rotation in the frontal plane. Consequently, compressive springs were not stretched and the closest point search algorithm identified points along the distal bone borders that were similar to locations of the distal ends of the springs for the two-end fixed model. However, the sliding RBSM took much longer to converge to a solution than the fixed-end RBSM. Although the simulation time was set at a maximum of 20 s (2000 steps × 0.01 s interval) the actual time for the fixed-end simulations was approximately one hour, while the shortest duration for the sliding models was greater than eighteen hours. Given the results for the healthy child were similar using both modeling methods, the longer time required of the sliding RBSM does not warrant its use in this particular case, and in general, may offer little benefit over the fixed-end method when estimating joint kinetics of a normal wrist. However, the sliding model did converge to a solution for JIA subject 2 elucidating the potential value of this method when applied to a pathologically malaligned wrist.

Another factor that should be considered when assessing the efficacy of the sliding RBSM is the computational expense of the method. For example, the sliding RBSM took much longer to converge to a solution than the fixed-end RBSM. Although the simulation time was set at a maximum of 20 s (2000 steps × 0.01 s interval) the actual time for the fixed-end simulations was approximately one hour, while the shortest duration for the sliding models was greater than eighteen hours. Given the results for the healthy child were similar using both modeling methods, the longer time required of the sliding RBSM does not warrant its use in this particular case, and in general, may offer little benefit over the fixed-end method when estimating joint kinetics of a normal wrist. However, the sliding model did converge to a solution for JIA subject 2 elucidating the potential value of this method when applied to a pathologically malaligned wrist.

The second purpose of this study was to examine joint reaction and ulnar directed forces during a simulated grasping maneuver for the healthy and three JIA subjects and to compare the proportion of force transferred through the radio-ulno-carpal joints. Two RBSM methods (i.e., fixed-end and sliding) were used to characterize joint contact loading patterns. It was hypothesized that radio-carpal forces would be smaller for the JIA subjects and the ulno-carpal forces greater due to an unloading of the radius as the carpus displaces towards the ulna. In addition, it was also hypothesized that ulnar directed force along the shear axis would be greater for the JIA wrists.

In general, carpal bone displacements for the healthy child were predominantly vertical in direction with a greater ulnar component noted for the JIA subjects. This observation (Fig. 4) is a commonly noted clinical symptom of the disease (Linscheid, 1971; Pirela-Cruz et al., 1993; Nieuwenhuis et al., 1999). Loading patterns for the JIA wrists differed from the pattern for the unimpaired subject and previously reported data for adult normal wrists (Schuind et al., 1995; Iwasaki et al., 1998). The proportion of force transferred through the radio-carpal joints was less for the JIA subjects than the healthy child, with the opposite pattern observed across the ulno-carpal joints. These observations corroborate our expectation that greater carpal ulnar translation would be noted for the JIA subjects. That is, as the carpus migrates towards the ulna, the radio-carpal joints become unloaded while the load across the ulno-carpal joints increases. This loading pattern was noted using both fixed-end and sliding RBSM methods. The proportion of force transferred through the radio-carpal joints (i.e., radio-scaphoid and radio-ulnae) using the fixed-end method was 73.5% and 80.2% for the JIA subjects and the healthy child, respectively. In contrast, the proportion of force transferred across the ulno-carpal joints were greater for the JIA wrists (JIA = 26.6% and healthy = 19.8%). A similar trend was noted for the sliding RBSM with 64.2% and 72.8% proportion of the force transferred through the radio-carpal joints for the JIA subjects and the healthy child, respectively, with 35.9% and 27.2% across the ulno-carpal joints. Another clinical symptom common of the arthritic wrist is a narrowing of the inter-carpal and carpo-metacarpal spaces. Loss of joint space can lead to larger than normal joint reaction forces between the capitate and ulnare and has been associated with Kienbock’s disease (Coe and Trumble, 1993). Results using both spring modeling methods revealed a greater proportion of force transferred across the capito-ulnare joint for the JIA subjects (29%) than for the healthy child (17%) and for normal adult subjects (Iwasaki et al., 1998).

As expected, a larger proportion of force was transferred through the ulno-carpal joints of the JIA wrists than the proportion of force through these joints in the healthy child. Although statistical inferences were not possible given the small sample size of this study, all JIA patients exhibited larger ulnar directed forces. It is important to address that the method used to determine the ulnar directed force was heavily dependent on the inclination angle of the radius. That is, the subject with the largest ulnar directed force (JIA 2) had the largest inclination angle and the subject with the smallest ulnar directed force had the shallowest angle. Inclination...
angles for the healthy and JIA subjects were 24°, 36°, 51° and 28° and are reported in the same order as the subjects listed in Table 2. The inclination angle for the healthy child (24°) was identical to normative data reported in the literature (Schuind et al., 1992). It is possible that different findings might have resulted in a different method that had been used to define the shear axis and/or determine the magnitude of the ulnar directed force. We chose to project the reaction forces as we did for two reasons. The first reason was the axis could be reliably defined from standard postero-anterior radiographs requiring little subjective involvement of the individual constructing the wrist models. The orientation of the axis differed by less than 1° when defined on multiple occasions for the same subject. The second reason this axis adopted, was that carpal ulnar displacement is believed to be related to the inclination angle of the radius (Linscheid, 1986). The inclination angle described by Linscheid is identical to the axis used in this study. This does not imply the method we used to resolve the ulnar directed force was ideal and we recognize that it is not the only method. We chose the previously described method for its consistency and physiological relevance in the context of ulnar translation.

It is difficult to ascertain which RBSM method is better for estimating loading patterns of the JIA wrist without first considering limitations of this study. First, our 2D representation of a 3D wrist is greatly simplified. We do not imply either method (i.e., fixed-end or sliding RBSM) is an accurate quantitative representation of the loading profile, especially when a complex 3D structure is represented in 2D as discussed by Ide et al. (1992). For example, note how the geometry of the carpal bones in the end-position is same as the geometry of the bones in the start position. This is the result of our simulation being 2D in nature with the final position of each carpal bone determined by simulation rather than determined experimentally from a loaded X-ray of the wrist. We would have expected the “shape” of certain carpal bones to change due to the projection of out of plane rotations (e.g., scaphoid) had a loaded X-ray been used. Loaded X-rays were not used for reasons discussed earlier. Also, notice how part of the scaphoid “invades” the boundary of the radius for subject JIA(3), with a more global invasion noted for JIA(2). This invasion is the result of not imposing constraints on the simulation prohibiting such an invasion. Such constraints are difficult to implement and greatly increase the time required for convergence. Similar invasions were evident in RSBM model reported by Schuind et al. (1995). Because compression of the individual springs is related to the displacements of the centroid of each adjacent bone, an alternate graphical representation of the starting and end-positions would be to simply display the cross-hairs used to define the center of mass of each bone to depict the translations and rotations. However, we chose to display the bone boundaries because they better describe how the wrist behaved as a whole rather than merely reporting the cross-hair start and end-positions. Another limitation of our study was that intrinsic and extrinsic ligaments were assumed to be fully functional providing normal restraining forces between carpal bones. Although loss of ligamentous integrity is known to occur in JIA (Swezey, 1971; Findley et al., 1983), relevant information regarding mechanical properties of the JIA wrist are not available and therefore could not be included in our models. In addition, metabolic and histochemical changes of the cartilage are known to occur in JIA (Rowland and Taleisnik, 1998) and likely affect the mechanical behavior of the wrist. These factors were not included in the present study. Future studies are needed to ascertain constitutive properties of ligaments and cartilage for the JIA wrist if RBSM methods are to be used to better model the magnitude and pattern of joint reaction forces.

In this study, the carpal bones were modeled as being rectangular in shape. This is a reasonable assumption that has been used before (Berger and Garcia-Elias, 1991). The goal here was to find the steady state (i.e., static) solution, which is not sensitive to differences in inertial parameters for the carpal bones. Small differences in inertial terms would only affect the gravitational forces on the carpus, which are negligible in this analysis.

When using the fixed RBSM approach, the analysis for JIA(2) did not converge on a solution, but instead diverged, resulting in the prediction that the hand slides off the distal forearm. Since we know this not to be the case, the analysis was considered to be inferior to that of the sliding model. This is not dependent on the criteria employed for an acceptable solution, as other stop criterion gave similar results (other than those that simply stopped before the divergence was very large). Thus, this problem seems to be rooted in the use of the fixed model when malalignment is severe. Of course, the sliding model was developed to alleviate these problems, as well as to make the model more physiological. That is, cartilage is only rigidly attached to one bone and allows the other bone forming the articulating surface to slide over it. Fixed-end models assume that the bones are joined by springs. While this makes sense for ligaments (as was done in both models), it is inappropriate for cartilage and yields noticeable errors for malaligned wrists.

At the onset of this project, several experimental methods that might be used to validate the simulation results were considered. After deliberation, it was decided that validating the modeling results experimentally would not be feasible. Post-mortem JIA subjects are simply not available for in vitro research. Another approach would be to take unloaded and loaded X-rays
(i.e., of the simulated grasp maneuver) and compare the model estimated final carpal positions relative to the loaded X-rays. However, there is no device that can apply the distribution of the grasp force to the metacarpals as they were loaded in the simulation. For this reason, taking X-rays with the hand in a grasp was not undertaken as a means of validating the simulated carpal end positions.

Interpreting the results of this study with the above cited limitations in mind, the data are in agreement with clinical observations of ulnar displacement and carpal crowding suggesting RBSM modeling of the JIA wrist does afford a qualitative insight into carpal joint loading patterns. It is premature to conclude the sliding model is a better approach for the JIA wrist, however, the robustness of the sliding model when subject to off-center loading of the carpal bones is promising and warrants further investigation.

To the best of our knowledge, the results of this study provide the first insight into the pattern of joint reaction and ulnar directed forces in the JIA wrist. Both RBSM modeling methods suggest a larger proportion of force is transferred through the ulno-carpal joint of the JIA wrist than for healthy subjects, with a less than normal proportion of force transferred through the radio-carpal joint. In addition, the ulnar directed forces along the shear axis defined in this study were greater for all three JIA subjects compared to values for the healthy child. These observations are what were hypothesized for an individual with JIA of the wrist.

5. Uncited References


