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Load dependence in carpal kinematics during wrist flexion *in vivo*

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Abstract

Objective. The hypothesis tested was that generation of torque at the wrist affects joint kinematics.
Design. An *in vivo* study of normal wrist kinematics during plantar flexion motion against a constant load was undertaken, using a custom-designed instrumented apparatus to track the motion of the hand during the task.
Background. Despite clinical observations of a relationship between motion-loading and pain in wrists affected by rheumatoid arthritis, there is little published literature on the *in vivo* kinematics of the normal human wrist under load.
Methods. Ten volunteers with no wrist pathology were tested while generating torques of zero, 1.1 and 2.2 N m in a planar, unidirectional flexion motion. Hand kinematics were computed using the Planar Rigid Body Method algorithm and an 8° angular step size. The finite radius of motion and the range and standard deviation of the residuals to a fitted second-order curve were used as indices of changes in the kinematics.
Results. The magnitude of both the range and standard deviation of the residuals were found to increase significantly with torque at the 95% confidence level.
Conclusions. The wrist does not behave like a smooth mechanism when generating torque. Load affects carpal kinematics.

Relevance

We propose that fluctuations in the finite radius of motion are the natural kinematic consequence of intercarpal motion known to occur during wrist flexion. Wrist kinematics may be particularly sensitive to load and joint integrity because orchestrated intercarpal motion depends on the soundness of articular and ligamentous structures, the first to be affected in joint degenerating conditions such as rheumatoid arthritis. Thus, wrist kinematics under load may be a key to characterizing joint integrity. In wrist pathologies, simple planar testing of carpal kinematics under reproducible and controlled joint torque conditions may be a useful way to assess joint involvement before the onset of gross dysfunction, and to evaluate treatment outcomes. © 1997 Elsevier Science Ltd. All rights reserved.

Key words: Wrist, joint, load, kinematics, *in vivo*

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Introduction

A simple method for characterizing the *in vivo* kinematic behaviour of the human wrist while moving under load may be of great benefit to clinicians, particularly those concerned with treatment outcomes and conditions such as rheumatoid arthritis.[1] Three-dimensional (3-D) motion analysis techniques are often invasive or expensive, and their interpretation relies heavily on definitions and conventions[2,3]. With a joint such as the wrist, which has at least two degrees of freedom, standardization of the task is necessary so that differences between subjects can be compared. The investigation of the effects of joint loading on the wrist adds more complexity.

Therefore, two-dimensional analysis of the kinematics of a standardized planar motion can provide useful information on joint kinematics. *In vivo* 3-D

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studies confirm that flexion–extension motion of the hand relative to the forearm is essentially planar in the normal wrist, but that the location of the axis of rotation is not fixed[3–5]. The point where the axis of motion intersects the reference plane is the instantaneous centre of rotation in the plane. The instantaneous trajectory of the limb segment can be described as rotation about this point, which is the fulcrum about which all musculotendinous units generate instantaneous torque in the plane[6]. Experimentally the finite, rather than instantaneous, centre of rotation is calculated from successive position and orientation data obtained at discrete angular motion intervals[7].

In the human wrist the carpal bones form an intercalated mechanical chain which is stabilized by conforming articular shapes and ligamentous restraints and which has been shown to be deformable at physiological loads[8,9]. In hand pathologies, the relationships between motion, pain and load in the wrist are of interest, but hard to quantify[10]. Few *in vivo* kinematic studies of the wrist have been conducted with the joint loaded, and none has compared kinematics at different load levels[11].

We hypothesized that wrist kinematics are affected by the compressive and shear forces in the joint which accompany the generation of wrist torque, and that kinematic changes might provide early indicators of altered joint function. The present work details the development of an instrumented spatial linkage for investigating the effect of load on the finite radius of motion of the normal wrist during planar flexion, and the results of tests in 10 normal subjects.

Methods

Apparatus

An instrumental planar linkage which could track and record the kinematics of wrist flexion under load was built (Figure 1). The apparatus consisted of a custom-moulded handle for each subject, connected to a forearm support by a set of case-hardened steel linkages with three degrees of freedom to allow free motion and rotation of the handle in a plane. The three degrees of freedom of the apparatus were independently articulated by high-quality linear and rotational bearings coupled to incremental optical encoders via timing belts and pulleys. Measurements from the optical encoders fully described the position and orientation of the handle in the plane of motion. The degrees of freedom were calibrated and found to have accuracies of 0.35 mm (linkage arm length), 0.22° (handle to linkage arm angle) and 0.63° (absolute handle orientation). The apparatus was mounted on a chair so that flexion in a right hand occurred about a roughly vertical axis. A suspended weight produced an extension torque via a circular cam (0.05 m radius).

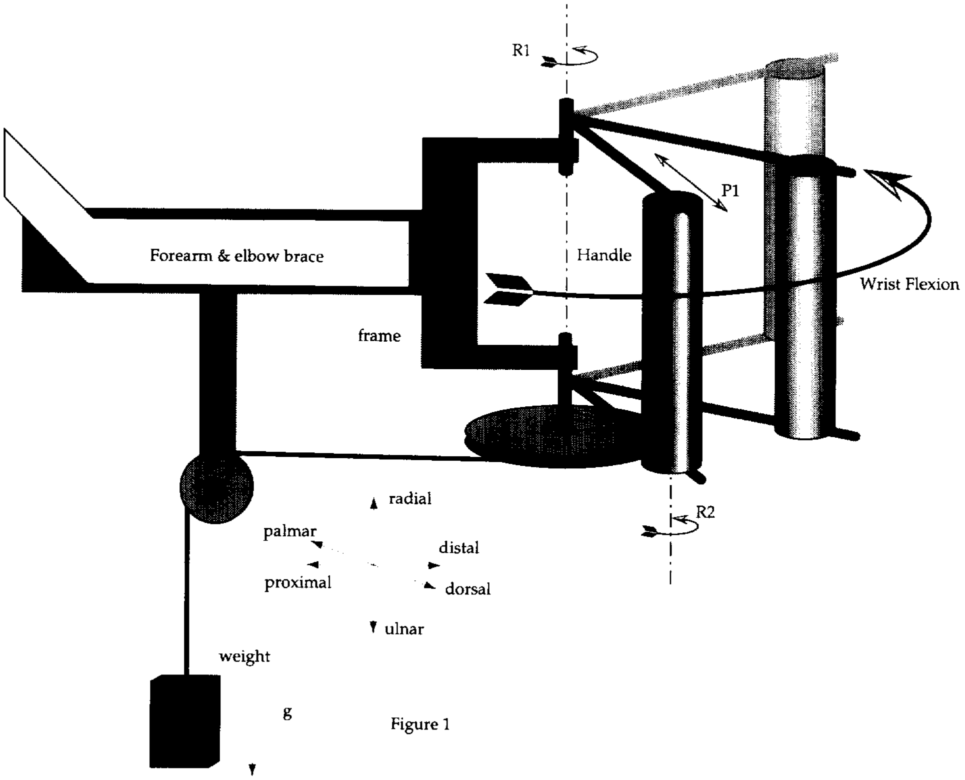

Figure 1. Schematic view of the instrumented spatial linkage apparatus, mounted on the right-hand side of a chair. The apparatus has one prismatic (P1) and two revolute (R1 and R2) joints that allow free motion in a horizontal plane, whether or not the wrist joint flexion axis of rotation is aligned with R1. The subject's arm was strapped to a forearm and elbow brace, and a suspended weight coupled to R1 provided torque at the wrist in opposition to the flexion motion.

The choice of weight generated torques of zero, 1.1 N m or 2.2 N m throughout the range of motion. Spatial linkages have been shown to accurately track motion of the limb[12]. The design produces accurate values for wrist motion, regardless of whether or not the wrist is aligned with the rotational joints of the linkage.

Experimental method

Ten healthy right-handed volunteers with no previous history of wrist pathology were recruited: five male, five female, mean age 25 (SD, 7) years. A custom-moulded handle was made for each, using a softened piece of thermoplastic splinting material wrapped around a wooden dowel. The handle was imprinted, and mounted on the apparatus after hardening. The plane of motion was set to be roughly 10° pronated and ulnarly deviated for comfortable wrist flexion[13], and the forearm was immobilized with wide Velcro® straps against a forearm and elbow brace. A weight was hung, pulling the handle against the physical stops at the subject's comfortably fully extended position. For each flexion trial, upon an audible signal, the volunteer fully grasped the handle against the palm and then slowly and smoothly flexed the wrist through the range of motion, lifting the weight. Subjects were instructed to maintain a constant grip throughout the tests, and trials were discarded if forearm, upper arm or torso movement occurred, or if the handle was not fully grasped. A typical flexion trial covered 80° and lasted 2 s, and was sampled at 2000 Hz by a data acquisition system and personal computer. Each subject performed a total of 24 flexions in a test–retest protocol. Four flexions were performed at each of three load levels, following which the subject was free to move from the apparatus for at least 20 min before retest. A load order of 1.1, 2.2, zero N m was followed in an attempt to familiarize subjects with the grip before the no-load trials.

Analysis

Custom software calculated handle position and orientation for each configuration recorded during a flexion trial, and the relative motion between paired handle configurations separated by a selected angular step size were examined with the Plantar Rigid Body Method (PRBM) algorithm[7]. The PRBM calculated the location of the finite centre of rotation of the two handle configurations. The distance from each pair's average position to the associated finite centre of rotation was defined as the finite radius of motion (Figure 2). In a two degree of freedom planar joint, a compliant hinge, an oblique hinge or a cam mechanism, the expected plot of finite radius against flexion angle is a smooth curve which can be approximated by a second-order polynomial. Variations in the magnitude of the finite radius over the course of the motion were used to characterize the deviation from a smooth curve, taken to be the least-squares second-order polynomial. The residuals to the polynomial (expected minus actual value) were computed, and two indices were used to compare kinematics: the residual range (extent of difference from the polynomial) and the residual standard deviation (characteristic difference from the polynomial). For comparison of subjects with varying hand sizes, these indices were normalized by dividing by the mean finite radius for the trial.

The experimental accuracy of the system was tested using two mechanical linkages to produce constant and smoothly varying finite radii of motion: a simple hinge and a four-bar linkage respectively. Angular step sizes of 4°, 8° and 16° were examined, and results confirmed that errors in the centre of rotation, and thus finite radius, are inversely proportional to angular step size and directly proportional to finite radius magnitude[7]. The 8° step size was selected as sensitive enough to detect changes in the wrist and large enough to produce acceptable uncertainties. A larger step acts to improve resolution in the PRBM, but smooths variations in the finite centre location, much as a moving average with a larger window. The experimental uncertainties in finite radius calculations (residuals to a second-order fit) for the 114 mm simple hinge were 1.9 mm and 0.55 mm in the residual range and standard deviation respectively. A simulation to assess artefact arising from soft-tissue compression in the hand was conducted using a 3 mm layer of foam rubber between the handle and the test linkage, at three load levels. Repeated measures analysis of variance (ANOVA) showed no significant differences in finite radius residual range and standard deviation with load, suggesting that compliance effects at the handle are minimal.

Results

Over the ten subjects, mean finite radii were 60 (SD, 8) mm and trial flexion ranges averaged 85° (SD, 7°). The handle trajectory was a smooth arc relative to the frame of reference in the apparatus. The path of the finite centre of rotation showed a slight increasingly palmarward drift and oscillations in the proximal–distal direction, which corresponded to changes in the length of the finite radius of rotation (Figure 2).

In the proximal–distal direction, motion of the forearm relative to the apparatus was not detected, yet the centre of rotation shifted during motion, up to 12 mm at the highest loads, reflecting changing proportions of translation and rotation in the motion of the hand relative to the forearm (Figure 3). The extent of the oscillations was characterized by the range and standard deviations of the residuals to a second-order polynomial fit of finite radius plotted against flexion angle. The steady palmarward shift in the finite centre of rotation during the test is believed to reflect a pivoting motion of the whole arm relative to the apparatus as the forearm muscles contracted. Tightening the Velcro straps any further would have been uncomfortable for the subjects. Hand motion in this direction relative to the apparatus was measured with a dial gauge to be 5–15 mm.

Repeated measures ANOVA found adjusted average normalized residual ranges for zero (0.121 (SD, 0.32)), 1.1 N m (0.143 (SD, 0.32)) and 2.2 N m (0.192 (SD, 0.32)) torques, and adjusted average normalized residual standard deviations for zero (0.028 (SD, 0.008)), 1.1 N m (0.034 (SD, 0.008)) and 2.2 N m (0.045 (SD, 0.008)) torques to be significantly different at the 95% confidence level. The pairwise Fischer protected least significant difference test found differences between the highest and the two lower loads at the 95% level. This analysis is designed to distinguish the effect of the treatment (i.e. load level) from effects due to subject differences (e.g. test–retest, inter and intrasubject differences).

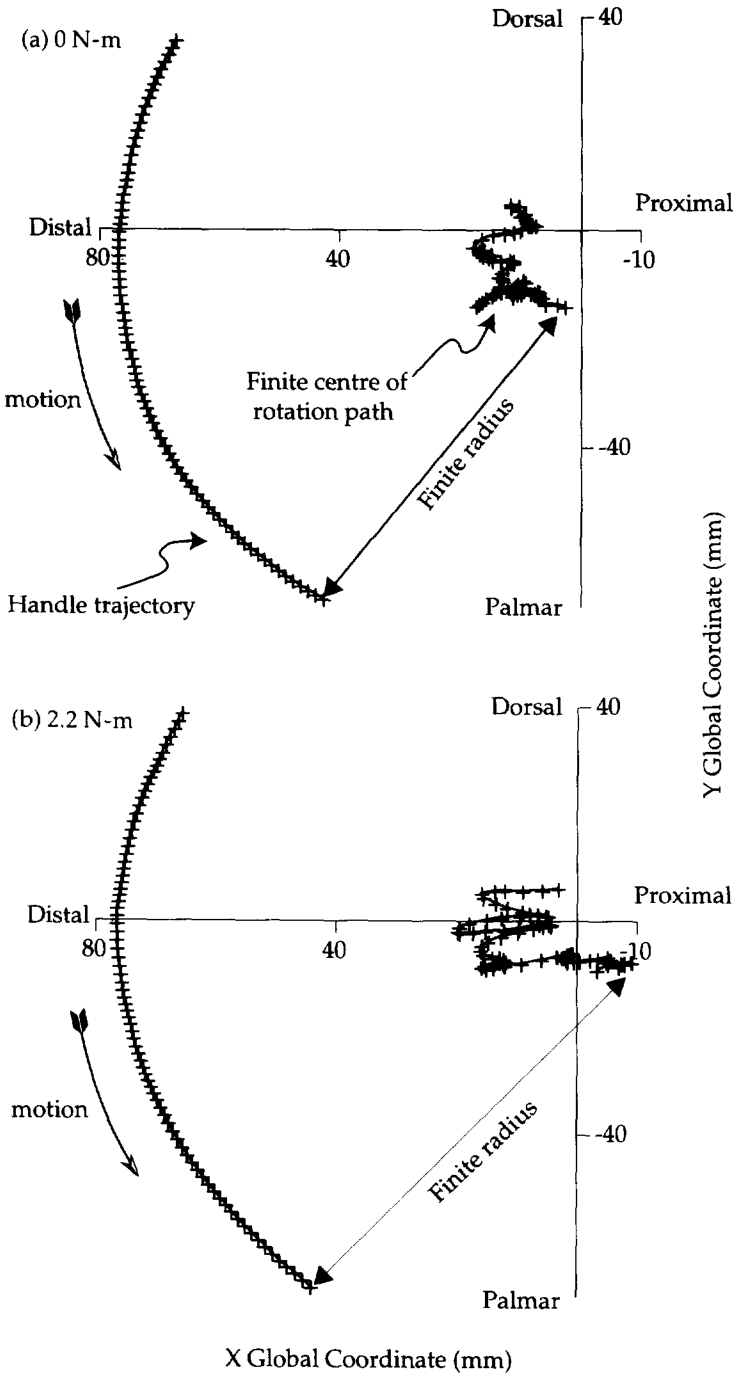

Figure 2. Trajectory and finite centre of rotation results at (a) no load and (b) 2.2 N m wrist torque. The Planar Rigid Body Method takes two handle positions, calculates their midperpendicular, and locates the finite centre of rotation as the distance between the centre of rotation and the midpoint between the two locations. We define the length of the finite radius of rotation as the distance between the centre of rotation and the midpoint between the two locations. The finite centre of rotation corresponding to the last finite centre for each trial is shown.

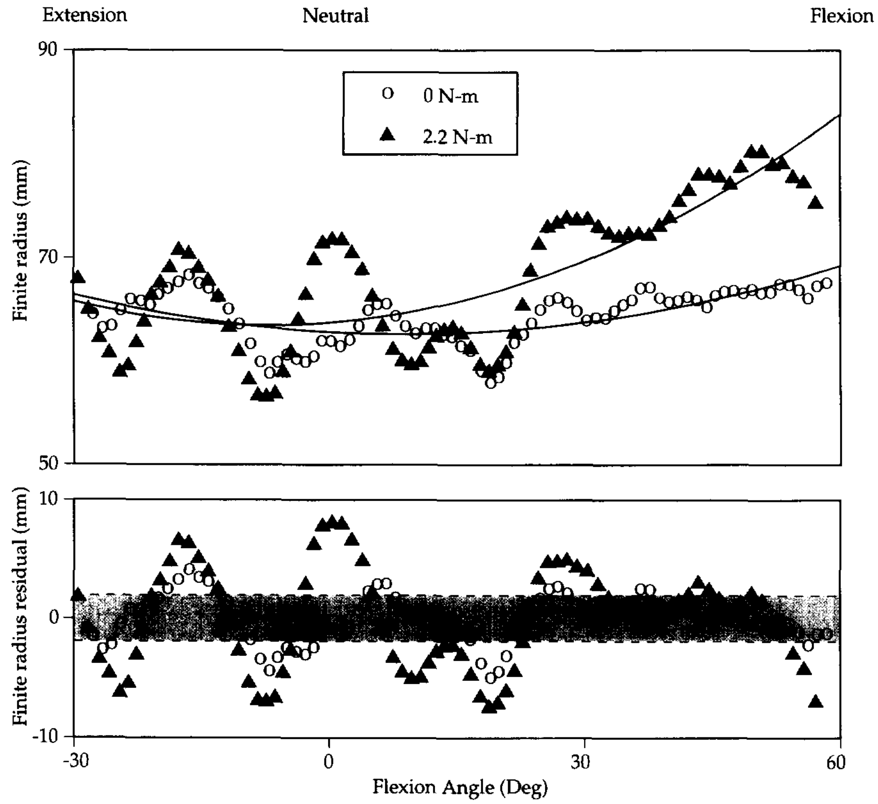

Figure 3. Finite radius vs flexion angle (top graph) and residuals from the fitted second-order least-squares polynomial (lower graph) for the two trials of Figure 2. The region between the dashed lines indicates experimental uncertainty in the residual range, as determined by the 114 mm fixed radius test link.

Discussion

Analysis of planar wrist flexion in 10 normal wrists reveals that the wrist does not have a constant or uniformly varying finite radius of rotation, and that loading the joint alters the kinematics. The generation of torque produces variations in the magnitude of the finite radius of rotation which tend to increase with load level. While there may be an effect of altered joint stiffness with loading, due to the combined effects of articular tissue, muscles and tendons, the contribution of joint stiffness changes to motion patterns is difficult to quantify and applies mostly when perturbing the joint from a nominally fixed position[14], and not when voluntarily flexing the joint in a unidirectional, smooth manner. A recent 3-D cadaver study, which tracked individual carpal bone motion during passive motion of the hand, found moving helical axes in flexion–extension, whether referred to the carpus or metacarpal unit[15]. In the present study, planar analysis of a planar motion revealed finite radius fluctuations which increased with load. The fluctuations were not significantly different between subjects at a given load. We postulate that the joint forces which accompany the generation of wrist torque induce more irregular carpal motion.

We propose that the fluctuations in the finite radius of motion are the natural consequences of intercarpal motions, known to occur during wrist flexion[1], inducing changing proportions of translation and rotation motion at the hand. The stable and orchestrated motion of the intercalated carpal bones is stabilized by articular and ligamentous structures known to be deformable at physiological loads[8,9]. Our results suggest that intercarpal motion, and thus finite radius of motion, are sensitive to the level of interarticular shear and compressive forces that accompany the production of joint torque. Therefore wrist kinematics under load may be particularly sensitive to joint integrity. Furthermore, changes in the finite radius reflect the motion of the finite centre of rotation without requiring invasive (e.g. radiographs, CT) or costly (e.g. MRI) techniques to locate the finite centre of rotation with respect to the bony anatomy.

Pathological joint changes such as ligament tears, bone resorption, carpal collapse, or subluxation such as rheumatoid arthritis can lead to gross changes in wrist kinematics[4,8,16]. This non-invasive method of assessing wrist kinematics under load could prove useful in eliciting differences between normal and affected wrists before pronounced radiographic or kinematic changes occur.

Conclusions

The present study used an instrumented spatial linkage to investigate the effect of load on the finite radius of motion of the normal wrist during flexion. Variations in the length of the finite radius of motion were used to characterize deviations of wrist kinematics from the expected smooth curve. Results showed that wrist kinematics are affected by joint forces, and suggest that in future altered kinematics under load could be a sensitive discriminator of joint dysfunction.

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