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Citation for published version (APA):
Lange, de, A., Huiskes, H. W. J., Kauer, J. M. G., & Woltring, H. J. (1985). On the application of a smoothing procedure in the kinematical study of the human wrist joint in-vitro. In *Biomechanics : current interdisciplinary research : selected proceedings of the fourth meeting of the European Society of Biomechanics / Ed. S.M. Perren, E. Schneider* (pp. 303-308). (Developments in biomechanics; Vol. 2). Nijhoff.

Document status and date:
Published: 01/01/1985

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

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41. ON THE APPLICATION OF A SMOOTHING PROCEDURE IN THE KINEMATICAL STUDY OF THE HUMAN WRIST JOINT IN-VITRO

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1. INTRODUCTION

In most biomechanical studies, the motions of a rigid body (e.g. bone) are described in terms of Euler rotation angles and translation vectors or in terms of helical axis (e.g. axis of rotation, screw axis). Each description has its own benefits. An attractive aspect of the helical axis representation is its illustrative quality, giving a more direct impression of the joint motion. Other advantages are that the helical axis facilitates relating joint kinematics to joint geometry and that the values for translations and rotations are invariant under a co-ordinate system transformation.

However, in contrast to Euler angles determination, the helical axis determination is excessively error-prone, as was shown previously (3). This is caused by equipment-related and deterministic (kinematical and geometrical) factors. In addition, helical axis determination is only possible when there is a substantial rotatory movement, since the helical axis vanishes under pure translation (3).

In terms of helical axis, the motion of a continuously moving rigid body is completely known once the translation and rotation velocities, and the position and direction of the instantaneous helical axis (I.H.A.) are known over time. In many motion studies, however, due to the facilities of the applied measuring techniques (e.g. ultrasonic digitization, cine-photogrammetry, roentgen-stereophotogrammetry), only samples of the continuous rigid body motions can be obtained. Hence, the continuous movement is approximated by sequential finite displacements. Using these techniques, the finite helical axes (F.H.A.) are estimated from position measurements on a number of anatomical or artificial landmarks. It has been shown theoretically that this approach yields finite helical variable estimates which are quite sensitive to measurement errors in the landmark co-ordinates (3).

From the deterministic point of view, it was shown (3) that errors in the position and direction of the F.H.A. are inversely proportional to the finite rotation magnitude. Unfortunately, however, small rotational increments are required in order to reliably approximate the continuous movement with finite displacement steps.

These considerations are of particular interest when the rigid bodies being studied are small, i.e. when the effective radius of the landmark distribution is small (as in the carpal bones of the wrist joint), and when the landmarks are not close to the helical axis. In this case the determination of the helical axis is notoriously error-prone (3).

It has been shown theoretically and by simulation (5) that the estimation of the I.H.A. and the F.H.A. can be performed at a much higher accuracy than would be feasible by traditional methods. The landmark displacement data can be treated as measurements on a continuous, bandwidth-limited movement process and the helical axes can be estimated following a smoothing procedure and, for directly estimating the I.H.A., a differentiation procedure. Such a differentiation procedure is not required when the F.H.A. is taken as an approximation for the I.H.A..

The purpose of the present research program is to generate accurate kinematic data with respect to the individual carpal bones of the wrist joint in several typical handmotions and to describe these motions using both Euler angle and helical axis descriptions. Whereas previous reports usually applied Euler angle descriptions (1,2), the present paper is focussed on the improvement of the F.H.A. estimates, using a smoothing procedure as outlined above.

2. MATERIAL AND METHOD

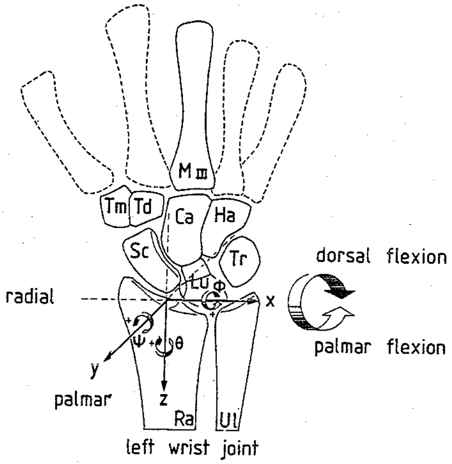

FIGURE 1. The reference co-ordinate system in the radius.

The motions of the individual carpal bone are determined by means of a previously described roentgen-stereophotogrammetric system (2,6). With this system, the spatial positions of 4 to 5 tantalum pellets (0.5-1.0 mm diameter), inserted in the seven carpal bones, in the radius and in the ulna (Fig.1) are determined for each specific motion step with an accuracy of 30-60 μm and used to determine relative changes in the bone positions. The experiments are performed with fresh human upper extremity specimens, three of which have been evaluated at the present time.

The specimens are mounted in a rig and the tendons of four palmar and four dorsal muscles are connected to stainless steel wires, each loaded by a 20 N constant-force spring.

Using a special motion-constraint device, the hand is moved in motion steps of 4 degrees from palmar to dorsal flexion and vice-verca, and from radial to ulnar deviation and vice-versa. In this fashion, approximately 20 samples of each prescribed deviation motion and approximately 40 samples of each flexion motion of the hand are obtained.

The rigid body motions of each carpal bone relative to the radius are determined in terms of Euler rotations about and translations along their co-ordinate axes (Fig.1) and also in terms of finite helical axes.

There are several methods for data smoothing available. For example, finite impulse response filters, splines (4,7) and those based on Fourier analysis (8). In the present investigation the algorithm of Utreras (7), based on quintic splines and optimal regularization theory, has been used. Quintic splines approximate the data by means of a set of piecewise polynomial functions which are continuous up to the third derivative. The algorithm of Utreras assumes in addition that the data have been sampled equidistantly; this assumption is fulfilled through the use of the motion-constraint device.

However, the algorithm of Utreras is only valid for sufficiently large record length, e.g. for a number of sampling points $n > 30$-40 (4). Hence, only the position data of the prescribed flexion of the hand (40 motion steps) have been treated with this smoothing procedure at this time.

Although the smoothed co-ordinates can be used in general for differentiation to obtain velocities and accelerations, in this study the smoothed data are only used to re-calculate the finite helical axis characteristics. The F.H.A.'s thus determined provide accurate estimates of the instanteneous helical axes, since the small-angle noise effect is substantially reduced by the smoothing procedure and since the finite angle is sufficiently small ($\approx .1$ rad).

3. RESULTS

For visual interpretation, the finite helical axes are plotted as projections onto two co-ordinate planes (Fig.2.a) and as intersections (piercing points) with the major plane of motion and two additional planes parallel to

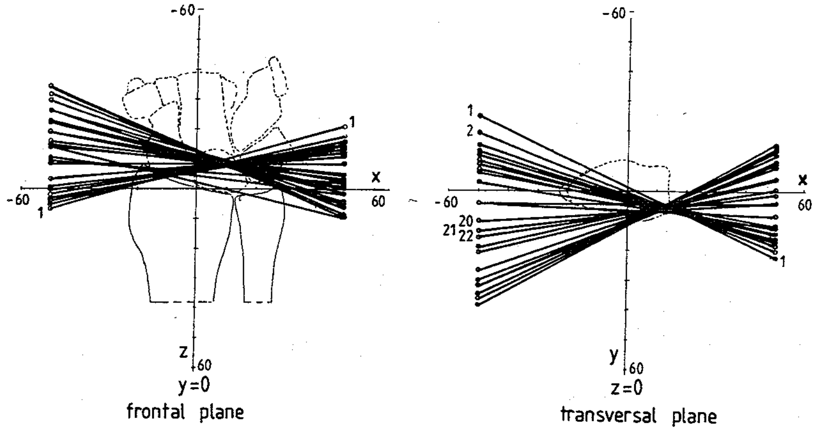

FIGURE 2. a. The helical axes as projections onto the co-ordinate planes of the reference co-ordinate system in the radius.

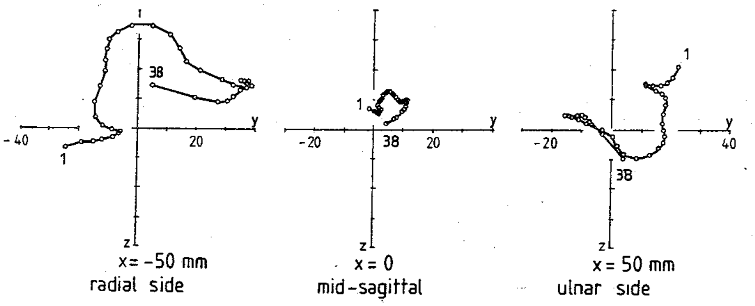

FIGURE 2. b. Pathway of the intersections of the helical axes for the lunate during flexion.

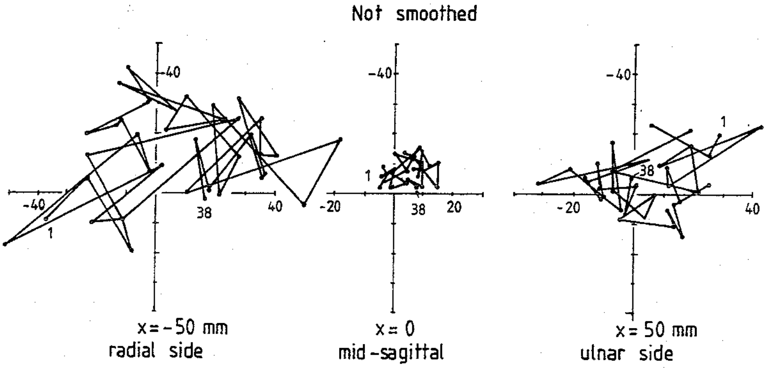

FIGURE 3. Pathways of the intersections of the finite helical axis with the major plane of motion (x=0) and two additional planes parallel to this major plane, for the lunate during flexion, resulting without the application of the smoothing procedure on the raw data.

this major plane (Figs.2.b and 3). The F.H.A.'s are calculated either directly from the relative rigid body displacement data (Fig.3), or from these data after smoothing of the relative landmark displacements (Fig.2). In the latter case, the true co-ordinates of the landmarks are modelled as bandwidth-limited, and the measurement errors are assumed to be uncorrelated over time and between co-ordinates, and to be additive, zero-mean, and stationary.

The helical axes as obtained without the smoothing (Fig.3; lunate relative to radius, flexion motion of the hand, specimen no.2) show a rather random bundle of finite helical axes for each carpal bone, which cannot be related to the assumed smoothness of the carpal bone motions; an assumption which is advocated by the obtained "smooth" Euler rotation results.

In order to estimate the influence of the spatial landmark reconstruction error (30-60 μm) on the kinematical parameters, two sequential roentgenograms of a dorso-palmar flexion series have been re-measured (4 degrees motion step, 4 pellets, approximately 5 mm effective radius of the landmark distributions). The standard deviations, obtained for specimen no.2, are presented in Table 1. Obviously, the error in the helical axis direction angle is very high, relatively speaking, which is also evident from Fig.3, and which is in close agreement with theoretical predictions (3).

	Symbol	Standard Deviation (degrees)
Euler rotation around		
x-axis	ϕ	0.13
y-axis	ψ	0.19
z-axis	θ	0.34
Direction angle of helical axis	$\underset{\sim}{n}$	8.55

Table 1. Standard deviation for a number of kinematic parameters, measured for specimen 2. Motion step 4 degrees (n=7).

For the same lunate motion, the finite helical axes as obtained after the smoothing procedure are shown in Fig.2. In contrast to the unsmoothed case, the helical axes shown in Fig.3 indicate a smooth motion pathway which is in agreement with the assumed continuous movement of the hand.

The spatial co-ordinates of the landmarks, before and after smoothing, have been mutually compared in the sense of the r.m.s. distance in the x-, y- and z-directions. The r.m.s. distances found for the four lunate landmarks are given in Table 2.

The values obtained are indeed in the order of the expected random error in the landmark co-ordinate determination.

	Landmark number 1	2	3	4
x	34	36	34	34
y	19	20	24	23
z	62	63	56	77

Table 2. The r.m.s. distances in µm between the lunate landmark co-ordinates, before and after smoothing.

4. DISCUSSION

In the present kinematical study on wrist-joint motions, the continuous motions of the carpal bones have been approximated by 4 degrees finite displacements of the hand through both flexion and deviation planes of motion. Whereas the kinematical results in terms of Euler rotation angles and translation vectors show excellent quantitative and qualitative reproducibility, those in terms of (unsmoothed) finite helical axes do not. This is due to the high influence of landmark measurement errors on the helical axis calculus, as has been shown experimentally (Table 1) and explained theoretically (3).

By smoothing the raw landmark position data first and thus filtering the noise (measurement errors) from the signal in a stochastic sense more consistent and useful finite helical axes can be obtained.

Although several assumptions (a.o. sampling distance, noise assumptions) and other smoothing methods are currently under investigation, it can already be concluded (see Fig.2 vs Fig.3) that the optimal regularized quintic splines method yields excellent results and seems to be suitable for reliable noise filtering (Table 2) in the present carpal bone motion study.

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