Title: A novel method to replicate the kinematics of the carpus using a six degree-of-freedom robot

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Abstract: Understanding the kinematics of the carpus is essential to the understanding and treatment of wrist pathologies. However, accurate measurement of the kinematics of the carpal bones is difficult because they are small bones undergoing complex movements of small amplitudes. As a result, to date, there is no clear consensus on carpal kinematics. Moreover, most studies only investigate single rotations of the wrist, whereas functional motions involve combined rotations. The present paper presents a novel method to reproduce functional wrist motions measured in vivo on cadaveric specimens, while at the same time measuring the kinematics of the carpal bones using K-wires. Results showed good accuracy (1.0 to 2.6°) of movement reproduction and kinematics measurement. Importantly the efforts at the wrist remained low during movement reproduction, further strengthening the validity of the method. Most carpal motion during wrist flexion-extension occurs at the radiocarpal level; while in ulnar deviation the motion is more equally shared between radiocarpal and midcarpal joints, and in radial deviation the motion happens mainly at the midcarpal joint. For all rotations the lunate exhibited more midcarpal motion compared to the scaphoid and triquetrum. For the functional motion studied (hammering), there was more midcarpal motion in wrist extension compared to pure wrist extension while radioulnar deviation patterns were similar to those observed in pure wrist radioulnar deviation. Finally, it was found that the amount of carpal rotations was proportional to global wrist rotations.
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**RE: Full length article submission**

We would like you consider the attached paper entitled “A novel method to replicate the kinematics of the carpus using a six degree-of-freedom robot” for submission to the Journal of Biomechanics.

We certify that this article is original, that it is not under consideration by another journal or been previously published. All named authors were involved in the conception of the idea, data collection, data analysis and drafting of the final manuscript.

Yours sincerely,

François Fraysse
Referee Suggestions

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A novel method to replicate the kinematics of the carpus using a six degree-of-freedom robot.

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Abstract

Understanding the kinematics of the carpus is essential to the understanding and treatment of wrist pathologies. However, accurate measurement of the kinematics of the carpal bones is difficult because they are small bones undergoing complex movements of small amplitudes. As a result, to date, there is no clear consensus on carpal kinematics. Moreover, most studies only investigate single rotations of the wrist, whereas functional motions involve combined rotations. The present paper presents a novel method to reproduce functional wrist motions measured in vivo on cadaveric specimens, while at the same time measuring the kinematics of the carpal bones using K-wires. Results showed good accuracy (1.0 to 2.6°) of movement reproduction and kinematics measurement. Importantly the efforts at the wrist remained low during movement reproduction, further strengthening the validity of the method. Most carpal motion during wrist flexion-extension occurs at the radiocarpal level; while in ulnar deviation the motion is more equally shared between radiocarpal
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1. **Introduction**

In order to understand the wrist, it is essential to understand the kinematics of the carpal bones (Gardner et al., 2006). However, many factors make measurement of carpal kinematics difficult (Garcia-Elias et al., 1989). The carpal bones are surrounded by multiple tendinous and ligamentous structures; they are small, of irregular shapes; and they undergo complex rotational and translational motions of small amplitudes. As a consequence, to date there is no clear consensus on the kinematics of carpal bones, meaning that pathomechanical models of wrist joint pathology are limited (Andrews and Youm, 1979; Craigen and Stanley, 1995; Nuttall et al., 1998).

Numerous anatomical studies have been performed in the past, which have involved dissection, arthroscopy or examination of radiographic images (McLean et al., 2006; Nakamura et al., 2001; Viegas, 1990; Viegas et al., 1993; Yamaguchi et al., 1998; Yazaki et al., 2008). Although anatomical studies provide invaluable information regarding the shapes and static relations of the carpal bones, they do not give insight into their motion. In an attempt to quantify the kinematics of the carpal bones, a number of methods have been used, medical imaging being by far the most common. Imaging allows both *in vivo* and *ex vivo* studies, using either plain radiographs (Berger et al., 1982; Craigen and Stanley, 1995; Galley et al., 2007; Haase et al., 2007; Kobayashi et al., 1997a; Kobayashi et al., 1997b; Nakamura et al., 2000; Nuttall et al., 1998; Sagerman et al., 1995), Computed Tomography (CT) (Crisco et al., 2005; Crisco et al., 1999; Kaufmann et al., 2006; Leventhal et al., 2010; Wolfe et al., 2000) or Magnetic Resonance Imaging (MRI) (Nakamura et al., 1999). The main advantage of imaging techniques is the ability to perform *in vivo* analyses. However, it is difficult to obtain high frame rate recordings of continuous motions.
In an attempt to overcome the limitations of static methods, some authors have used bone pins to measure carpal kinematics (Patterson et al., 1998; Short et al., 2002; Werner et al., 2004; Werner et al., 2005). Bone pins allow accurate, real-time recording of carpal kinematics. However, they are limited to ex vivo studies. Moreover, the insertion of bone pins disrupts, at least partially, the integrity of the connective tissues surrounding the wrist, thereby affecting its kinematics (Short et al., 2002). They are also often limited by the type of motion reproduced: most commonly, pure single-rotation motions are studied (Kobayashi et al., 1997a; Werner et al., 1996). However, many activities of daily living involve combined rotations of the wrist, which functional movement is often described as through the dart’s throwers arc (Gardner et al., 2006). The aim of this study was therefore to develop an accurate and reproducible ex vivo model of carpal kinematics.

2. Material and Methods

2.1. Summary

The study received ethics approval from institutional human research ethics committees. Eight fresh cadaveric upper limb specimens were used. K-wires (‘bone pins’) were inserted into the forearm and carpal bones, and retroreflective markers were fixed on the bone pins. CT scans of each specimen were taken and reconstructed. The specimens were then mounted on a 6-DoF Stewart platform (‘Hexapod’) (Ding et al., 2011), see specifications in Table 1), and moved through a series of wrist motions: flexion-extension, radio-ulnar deviation and hammering. The latter was obtained from an in-vivo experiment and resembles the dart thrower’s arc (see §2.3).
2.2. Definitions

The forearm and hand Anatomical Coordinate Systems (ACS) $^{0}_T{\text{fore}}$ and $^{0}_T{\text{hand}}$ are defined in Table 2. The global wrist angles are the rotations from the forearm to the hand ACS, following a ZY’X’’ sequence. Wrist flexion-extension $\theta_{FE}$ and radio-ulnar deviation $\theta_{RUD}$ are the rotations about the Z ($Z_F$) and X’’ ($X_H$) axes, respectively. The carpal bones ACS were defined as aligned with the forearm ACS when both $\theta_{FE}$ and $\theta_{RUD}$ angles were zero. Rotation sequences and angles definitions were the same as for the global wrist angles.

2.3. In vivo data collection

Twenty-one healthy volunteers (12 male, 9 female, age 29.9±9.5 years, height = 1.80±0.10 m, mass = 76.4±16.8 kg) participated. Written informed consent was obtained before data collection. Fifteen retroreflective markers were placed on the upper arm, forearm and hand and used to define the forearm and hand ACS (Table 2). Participants were asked to strike a rubber block using a standard hammer. Hammering frequency was set at 1 Hz and controlled with a metronome. Five, 10-second trials were recorded per subject. Marker trajectories were recorded at 100 Hz using a 12-camera optoelectronic motion capture system (Optitrack®, Natural Point, USA) and low-pass filtered at 6 Hz using a 4th order, zero-lag Butterworth filter. The wrist joint angles were computed over each cycle, and the mean for all subjects was calculated (Figure 1A).
2.4. Specimen preparation

Eight fresh cadaveric upper limb specimens were used. Bone pins were inserted by an orthopaedic surgeon into the distal ulna and radius, 3rd metacarpal, scaphoid, lunate, triquetrum and capitate (Figure 2A). Pin positioning was initially confirmed using plain film radiographs and later by CT scans. Skin incisions were made on the back of the hand to help locating the carpal bones. All ligaments and other soft tissues were left intact. CT scans of the cadavers were then taken (slice thickness 0.5 mm, no slice gap). The wrists were then individually packaged to avoid any movement of the pins and refrozen.

Three-dimensional surface models of the bones were reconstructed from the CT data using ScanIP (Simpleware, Exeter, UK) (Figure 2B) and exported to Matlab (R2011b, The Mathworks Inc.). For each bone in which a pin was inserted, a technical coordinate system (TCS) was created. The following TCS where created: $^0_{\text{ForeT}} T$, from the radius, 3rd metacarpal, scaphoid, lunate, triquetrum, and capitate pins, respectively. Additionally, the following anatomical landmarks were identified on the 3D reconstructions: medial and lateral humeral epicondyles, radial and ulnar styloids and the base and head of 2nd and 5th metacarpals. These landmarks were used to define the forearm and hand ACS $^0_{\text{ForeT}} T$ and $^0_{\text{handT}} T$ (see Figure 2B). Transformation matrices from the forearm and hand TCS to ACS were then calculated as:

$$^0_{\text{ForeT}} T = 0_{\text{ForeT}} T^-1 \times 0_{\text{ForeT}} T,$$

and

$$^0_{\text{handT}} T = 0_{\text{handT}} T^-1 \times 0_{\text{handT}} T.$$
we hypothesised that the global wrist motion was a 2-DoF rotational motion, the centre of rotation being the midpoint between the most distal tip of the lunate and the most proximal tip of the capitate (Youm et al., 1978), here called Wrist Joint Centre (WJC). This point was identified on the CT reconstructions for each specimen and expressed in both $^{0}_{ForeA}T$ and $^{0}_{HandA}T$. From this, and knowing the time history of the wrist FE and RUD angles, as well as the value of the (fixed) wrist axial rotation angle, the pose matrix $^{ForeA}_{HandA}T$ was computed. Note that the hypothesis of a fixed wrist rotation centre was made only to reproduce the desired motions. When reconstructing motion from captured data the hand was considered to have 6 DoF relative to the forearm.

Three wrist motions were tested: 1) Flexion-extension. For this motion the RUD angle was kept at 0° while the FE angle followed a sine form, starting at 0°, moving into 15° flexion, then 15° extension, and back to 0°. 2) radio-ulnar deviation, which followed the same principle, with the FE angle kept constant at 0° and the RUD angle following a sine form from 20° ulnar deviation to 20° radial deviation. 3) The hammering motion obtained from the in vivo experiment. The hammering motion reproduced was 50% of the average in vivo wrist angles. For all three motions the wrist axial rotation angle (around Y’) was kept constant at the value obtained from the CT scans.

Using the input wrist angles and the position of the WJC, the transformation matrix $^{ForeA}_{HandA}T(t)$ was computed. Subsequently, using the transformation matrices $^{ForeA}_{ForeT}T$ and $^{HandA}_{HandT}T$ obtained from the CT reconstructions, the pose of the hand TCS relative to the forearm TCS $^{ForeT}_{HandT}T(t)$ was computed for each specimen and each motion as:

$$^{ForeT}_{HandT}T(t) = ^{ForeA}_{ForeT}T \times ^{ForeA}_{HandA}T(t) \times ^{HandA}_{HandT}T^{-1}.$$
2.6. *Ex-vivo experiment*

Each specimen thawed 12 to 16 hours prior to the experiment. During preparation, the phalanges were disarticulated and the radius and ulna were transected at their distal third, so that the distance between proximal and distal ends of the specimen was 280 mm. Skin and soft tissues were removed from the proximal 50 mm of the forearm, and on the distal half of the metacarpals.

The specimen was mounted in a custom-built alignment device to ensure repeatable mounting. The radius and ulna were positioned inside an aluminium pot (diameter 75 mm, depth 70 mm) and fixed in polymethylmethacrylate (PMMA). The specimen was then turned upside-down and the metacarpals were placed in another aluminium pot (diameter 120 mm, depth 45 mm) and fixed in PMMA (Figure 3A). The specimen was then mounted in the Hexapod with rigid fixings (Figure 3B). Twelve retroreflective markers were placed on the Hexapod, six on the base and six on the end-effector, defining the hexapod base and end-effector TCS. A 2s static capture trial was then recorded, from which the pose matrices $^{\text{Base}}T_{\text{Fore}}$ and $^{\text{End}}T_{\text{Hand}}$ were computed as:

$$^{\text{Base}}T_{\text{End}}^{-1} = ^{\text{Base}}T_{\text{Fore}}^{-1} X ^{\text{Base}}T_{\text{Fore}}$$

These matrices represent the pose of the Hexapod base and end-effector TCS relative to the forearm and hand TCS, respectively, and were constant for each specimen.

Finally, the pose matrix $^{\text{Hand}}T_{\text{Base}}(t)$ (see §2.5) was used to obtain the pose of the hexapod end-effector relative to its base from:

$$^{\text{End}}T_{\text{Base}}(t) = ^{\text{Hand}}T_{\text{Base}}^{-1}(t) X ^{\text{Hand}}T_{\text{Base}}(t)$$

The time-varying pose matrix $^{\text{Base}}T_{\text{End}}(t)$ was used to drive the Hexapod robot.
All movements were performed over a 10s duration (for the hammering motion this corresponds to 1/10th of the in vivo speed) and each cycle was repeated three times (Figure 1B). Marker trajectories were recorded using a 12-camera Vicon MX-F20 motion capture system (Vicon, Oxford, UK) at 100 Hz.

From the marker trajectories, the ACS were reconstructed. From the bones ACS the following angles were computed: 3rd metacarpal relative to radius (global wrist angles); scaphoid, lunate and triquetrum relative to radius (radiocarpal angles); capitate relative to scaphoid, lunate and triquetrum (midcarpal angles); and 3rd metacarpal relative to capitate (carpometacarpal angles). The means and standard deviations over repetitions and specimens were calculated.

The RMS error between the input and measured global wrist angles were also computed as:

$$RMS_{\epsilon}(\theta) = \sqrt{\frac{\sum_{t} (\theta_M(t) - \theta_I(t))^2}{T}}.$$  

Where $\theta_I$ and $\theta_M$ are the input and measured wrist joint angle and T the duration of the repetition.

The ratios of carpal rotation to global wrist rotation were calculated for the following wrist displacements: from 0° to 15° of flexion and 0° to 15° of extension for the flexion-extension motion; from 0° to 20° of ulnar deviation and 0° to 20° of radial deviation for the radio-ulnar deviation motion. For the hammering motions the ratios were computed from 0° to maximal wrist flexion (7.1°), extension (11.1°), ulnar (13.6°) and radial (4.8°) deviation, respectively.

In order to investigate whether the ratio of carpal rotation ($\theta_C$) to wrist rotation ($\theta_W$) was constant over the tested range of motion, a linear curve was fitted to the experimental data $\theta_C = f(\theta_W)$, and the $r^2$ of this fit was computed.
Forces and moments were recorded at 1000 Hz using a six-axis load cell (MC3A-6-1000, AMTI, MA) mounted at the hexapod end-effector, lowpass filtered at 20 Hz, transposed at the WJC and expressed in the forearm ACS. RMS variations were computed as:

\[ \text{RMS}_y(F) = \sqrt{\frac{\sum_{t=1}^{T} (F(t) - \bar{F})^2}{T}}, \]

Where \( F(t) \) is the effort considered (force or moment) and \( \bar{F} \) the average of this effort over one repetition.

3. Results

3.1. Accuracy of movement reproduction

The average RMS errors between input and measured wrist angles are presented in Table 3. The largest RMS errors were observed for the measured flexion-extension angle with values of 1.8°, 2.6° and 2.0° for the FE, RUD and hammering motions, respectively. The RUD motion showed the highest RMS errors with values of 2.6° and 1.3° for FE and RUD angles respectively.

These errors have two main sources: the accuracy of the motion capture system and that of the Hexapod. The displacement accuracies of the Hexapod are orders of magnitude smaller than the RMS errors (see Table 1). For this reason, it is safe to assume that the vast majority of the error comes from the accuracy of the motion capture process. As a result, it was considered that all measured angles with a total range of variation of less than 2° were below measurement error and therefore not meaningful; referred to as negligible in the present paper.
3.2. **Efforts at the wrist**

Average, range and RMS variation of the efforts are presented in Table 4. The highest force acting on the wrist was ulnar shear (\(F_x\)), with an average value of 15.7 N for FE, 19.3 N for RUD and 12.7 N for hammering. The antero-posterior shear (\(F_z\)) was comparatively lower with averages of 6.6, 7.2 and 3.2 N. Axial compression (\(F_y\)) was the lowest, with averages of 4.7, 5.7 and 5.0 N. The RUD motion exhibited the highest forces overall. The highest moment component was flexion-extension (\(M_z\)) with averages of -1.5, -2.0 and -1.1 N.m for FE, RUD and hammering, respectively. Average radio-ulnar deviation moments all remained below 1 N.m. Finally, axial rotation moments were zero on average for all three motions with ranges of variation of 0.1, 0.4 and 0.2 N.m for FE, RUD and hammering respectively.

3.3. **Carpal kinematics**

In wrist flexion (Figure 4A) and extension (Figure 4B) the majority of carpal motion happened at the radiocarpal level. Relatively to the radius, the scaphoid, lunate and triquetrum flexed by 88% (SD 12%), 50% (SD 21%) and 68% (SD 7%) of global wrist flexion and extended by 84% (11%), 49% (6%) and 69% (8%) of global wrist extension, respectively. At the midcarpal level, the capitate flexed by 32 % (22%) and 15% (8%) of global wrist flexion relative to the lunate and triquetrum respectively, while the flexion relative to the scaphoid was negligible (i.e. <2°); and extended by 32% (29%) of global wrist extension relative to the lunate while its extension relative to the scaphoid and triquetrum was negligible. Carpal flexion varied linearly with global wrist flexion, with a minimum value of \(r^2\) of 0.823, and all correlations were found significant (p<0.05).

In ulnar deviation (Figure 4C) the radiocarpal joints accounted for the majority of the motion again, although the effect was less pronounced than for flexion-extension. In radial deviation
(Figure 4D) the opposite effect was observed with the majority of the motion occurring at the midcarpal level. Relatively to the radius, the scaphoid, lunate and triquetrum deviated ulnarly for 63 % (9 %), 41% (8%) and 71% (3%) while the capitate deviated ulnarly for 30 % (9 %), 52% (8%) and 22% (3%) of global wrist ulnar deviation relatively to these bones. In radial deviation, the scaphoid and triquetrum deviated radially by 23% (7%) and 49% (5%) of global wrist radial deviation relatively to the radius, while the lunate RUD was negligible. In the midcarpal row the capitate deviated radially for 58% (14%), 86% (14%) and 34% (14%) of global wrist radial deviation relative to the scaphoid, lunate and triquetrum, respectively. Again, carpal rotations were proportional to wrist rotations (minimum r² = 0.854, p<0.05).

Regarding out-of-plane rotations, the only rotations found non negligible were scaphoid/radius radial deviation during wrist extension (18% of wrist extension, SD=9%), and scaphoid/radius and lunate/radius flexion during wrist radial deviation (28±16% and 28±17% of wrist radial deviation respectively).

During the hammering motion, the majority of the scaphoid and triquetrum flexion-extension motion occurred at the radiocarpal level (Figure 5A, B). Relative to the radius, the scaphoid and triquetrum flexed by 64% (11%) and 81% (15%) of wrist flexion, and extended by 59% (13%) and 56% (11%) of wrist extension, respectively. At the midcarpal level, the capitate flexed by 37% (26%) of total wrist flexion and extended by 25% (13%) of total wrist extension with respect to the scaphoid. Capitate/triquetrum flexion was negligible while capitate/triquetrum extension was 28% (17%) of total wrist extension. The lunate exhibited an opposite behaviour: in wrist flexion lunate/radius flexion was negligible while capitate/lunate
flexion was 95% (39%) of total wrist flexion. In wrist extension, lunate/radius extension was 40% (8%) and capitate/lunate was 44% (18%) of total wrist extension. In ulnar deviation (Figure 5C), scaphoid, lunate and triquetrum ulnar deviations relative to the radius were 56% (14%), 38% (16%) and 75% (7%) of total wrist ulnar deviation. The capitate deviated ulnarly by 32% (17%) and 49% (16%) relatively to the scaphoid and lunate while its RUD relative to the triquetrum was negligible. In radial deviation (Figure 5D) only the triquetrum exhibited non-negligible motion relatively to the radius, with a radial deviation of 66% (27%) of total wrist radial deviation. At the midcarpal level the capitate deviated radially by 70% (24%) and 45% (60%) relatively to the scaphoid and lunate, while its RUD relative to the triquetrum was negligible.

4. Discussion

4.1. Evaluation of the motion reproduction method

We made the assumption that the global motion of the wrist occurred about a fixed centre of rotation. This assumption was necessary to allow reproducing the same joint angles on specimens of different dimensions. If this assumption was too coarse, or the estimation too inaccurate, it would have resulted in high loads at the wrist during motion reproduction, possibly damaging the specimens. However, as shown in §3.2, the efforts at the wrist remained small. Data on passive wrist moments are scarce in the literature; one study (Sinkjær and Hayashi, 1989) reports wrist angular stiffness of 0.21 N.m/degree over the whole flexion-extension range of motion, and another one (Leger and Milner, 2000) reports passive stiffness of 0.03 N.m/degree for a small amount (3°) of wrist flexion. In our case, for rotations of 15° in flexion and extension, those values would yield passive moments of 3.15 N.m and 0.45 N.m, respectively. The wrist flexion-extension moments recorded in the present
study are in the order of magnitude of these reported passive moments. This strengthens our
initial hypothesis of the approximate location of the WJC.

The average RMS differences between the input and recorded wrist angles were 2.1° and 1.1°
on average for flexion-extension and radio-ulnar deviation, respectively. RMS errors in the
order of 1° are consistent with the values of 2.4° to 4.1° reported by Chiari et al. (2005) for
the estimation of lower limb joint angles during gait. The smaller errors obtained in our study
may be a result of the smaller capture volume. Overall, the method employed in this study
allows reproducing and recording motions obtained from in-vivo experiments on cadaveric
specimens with high accuracy.

4.2. Kinematics of the carpal bones

During wrist flexion-extension, the majority of the carpal motion occurs at the radiocarpal
level. The flexion-extension of the central column is distributed between radiocarpal
(radiolunate) and midcarpal (lunocapitate) joints whereas the vast majority of scaphoid and
triquetrum flexion-extension occurs at the radiocarpal joint. This is in agreement with the
results of previous studies (Berger et al., 1982; Garcia-Elias et al., 1989; Kobayashi et al.,
1997a). Conversely, carpal motion in radio-ulnar deviation is more equally shared between
radiocarpal and midcarpal joints. In ulnar deviation, there is more motion of the scaphoid and
triquetrum at the radiocarpal than at the midcarpal level, whereas for the lunate, motion at the
midcarpal (lunocapitate) level dominates. In radial deviation, most of the motion occurs at the
midcarpal level, but once again, the lunate shows the least rotation relative to the radius
compared to the scaphoid and triquetrum, and the radiolunate rotation was negligible, in
agreement with the findings of Garcia-Elias et al. (1989). Kobayashi et al. (1997a) reported
similar findings but in radial deviation only. Additionally, we found that the scaphoid and
lunate flexed during wrist radial deviation. The amount of flexion and radial deviation of the
scaphoid were comparable in magnitude, whereas for the lunate, flexion was of greater
magnitude than radial deviation (which was negligible). However those bones did not show a
significant flexion-extension motion during ulnar deviation which was observed by Berger et
al. (1982).

Finally, the rotations of the carpal bones were proportional to the global rotation of the wrist
over the ranges of motion studies. This was also observed by (Kobayashi et al., 1997a) over
larger ranges of motion (60° of flexion and extension, and 30° of ulnar deviation). Therefore
it seems justified to infer carpal kinematics from recordings of static postures of the wrist, as
in Crisco et al. (2005).

The methods presented here are not without limitations. The range of motion was limited by
the capacities of the Hexapod robot. This was not a major concern in radio-ulnar deviation,
where the rotations attained were very close to the total physiological range of motion. It did
however limit the amount of flexion-extension to ±15° whereas the physiological range of
motion is ±60°. For the same reason the hammering motion had to be scaled down to 50% of
the actual in vivo values, potentially preventing the observation of changes in kinematics
occurring at the extremes of motion. Additionally, the method used did not allow controlling
the force applied to the wrist. It has been shown that axial loading modifies carpal kinematics
(Kobayashi et al., 1997b), therefore controlling the amount of axial load on the wrist during
motion reproduction may lead to kinematics closer to physiological reality.
References


Table titles

Table 1: Specification of the Stewart platform (Hexapod robot) tested for sine waveforms of frequency 0.1 Hz and amplitudes ± 1 mm (for translations) and ± 1° (for rotations).

Table 2: Definition of coordinate systems for the forearm and hand.

Table 3: RMS differences between command and measured wrist angles. Average over repetitions and subjects.

Table 4: Range, average and RMS variation of forces and moments acting at the wrist joint centre during each of the reproduced movements.
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Figure 1: A. Input wrist angles for the hammering motion (average of the angles measured in vivo). B. Time history of input wrist angles, including the initial positioning phase, the 3 repetitions and the pauses between them. Note the pronation-supination angle is kept constant.

Figure 2: A. prepared specimen with bone pins inserted. B. reconstructed CT scan including bone pins.

Figure 3: A. preparation and fixation of the arm prior to mounting in the Hexapod robot. B. Specimen mounted in the Hexapod robot ready for testing.

Figure 4: Ratios of carpal FE to wrist FE rotations, for A. 0 to 15° of wrist flexion; B. 0 to 15° of wrist extension; and of carpal RUD to wrist RUD rotations, for C. 0 to 20° of wrist ulnar deviation; D. and 0 to 20° of wrist radial deviation. Average and SD for all specimens. The numbers on the bars are the $r^2$ between the experimental curve $\theta_C = f(\theta_W)$ and the linear fit to it (see § 2.6.). No value indicates that the amplitude of bone rotation was negligible (i.e. < 2°, see § 3.2.). SCA: scaphoid, LUN: lunate, TRI: triquetrum, CAP: capitate, MET: 3rd metacarpal.
Figure 5 - Ratios of carpal FE to wrist FE rotations during hammering for A. 0 to 7.1° of wrist flexion; B. 0 to 11.1° of wrist extension; and of carpal RUD to wrist RUD rotations for C. 0 to 13.6° of wrist ulnar deviation; D. 0 to 4.8° of wrist radial deviation. Average and SD for all specimens. The numbers on the bars are the $r^2$ between the experimental curve $\theta_C = f(\theta_W)$ and the linear fit to it (see § 2.6.). No value indicates that the amplitude of bone rotation was negligible (i.e. $< 2^\circ$, see § 3.2.). SCA: scaphoid, LUN: lunate, TRI: triquetrum, CAP: capitate, MET: 3rd metacarpal.
Table 1: Specification of the Stewart platform (Hexapod robot) tested for sine waveforms of frequency 0.1Hz and amplitudes ± 1 mm (for translations) and ± 1° (for rotations).

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Table 2: Definition of coordinate systems for the forearm and hand.

<table>
<thead>
<tr>
<th>Forearm</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>O_F</td>
<td>Midpoint between radial and ulnar styloid processes</td>
</tr>
<tr>
<td>X_F</td>
<td>Cross-product between Y_F and functional FE axis (anterior positive)</td>
</tr>
<tr>
<td>Y_F</td>
<td>Functional PS axis (superior positive)</td>
</tr>
<tr>
<td>Z_F</td>
<td>Cross-product between X_F and Y_F (lateral positive)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hand</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O_H</td>
<td>Midpoint between proximal heads of 2^{nd} and 5^{th} metacarpals</td>
</tr>
<tr>
<td>X_H</td>
<td>Cross-product of Y_H and vector from proximal 5^{th} to 2^{nd} metacarpals (anterior positive)</td>
</tr>
<tr>
<td>Y_H</td>
<td>From the midpoint between distal heads of 2^{nd} and 5^{th} metacarpals to O_H</td>
</tr>
<tr>
<td>Z_H</td>
<td>Cross-product between X_H and Y_H (lateral positive)</td>
</tr>
</tbody>
</table>
Table 3: RMS differences between command and measured wrist angles. Average over repetitions and subjects.

<table>
<thead>
<tr>
<th></th>
<th>FE</th>
<th>RUD</th>
<th>HAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS&lt;sub&gt;FE&lt;/sub&gt; (°)</td>
<td>1.8</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>RMS&lt;sub&gt;RUD&lt;/sub&gt; (°)</td>
<td>1.0</td>
<td>1.3</td>
<td>1.0</td>
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</table>
Table 4: Range, average and RMS variation of forces and moments acting at the wrist joint centre during each of the reproduced movements.

<table>
<thead>
<tr>
<th></th>
<th>$F_X$ (N)</th>
<th>$F_Y$ (N)</th>
<th>$F_Z$ (N)</th>
<th>$M_X$ (N.m)</th>
<th>$M_Y$ (N.m)</th>
<th>$M_Z$ (N.m)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Avg</td>
<td>RMS</td>
<td>Range</td>
<td>Avg</td>
<td>RMS</td>
</tr>
<tr>
<td>FE</td>
<td>4.8</td>
<td>15.7</td>
<td>4.5</td>
<td>22.9</td>
<td>4.7</td>
<td>5.7</td>
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<td>24.8</td>
<td>6.6</td>
<td>2.1</td>
<td>1.0</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>-1.5</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUD</td>
<td>12.4</td>
<td>19.3</td>
<td>1.0</td>
<td>25.4</td>
<td>5.7</td>
<td>1.5</td>
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<td>7.2</td>
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<td>1.9</td>
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<td>1.7</td>
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<tr>
<td>Hammering</td>
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<td>12.7</td>
<td>0.7</td>
<td>10.7</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
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<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>-1.1</td>
<td>0.0</td>
</tr>
</tbody>
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The authors have no conflicts of interests to declare.