Determination of the number of degrees of freedom of the trapeziometacarpal joint–An in vitro study

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Received 29 January 2012; received in revised form 8 May 2012; accepted 2 July 2012
Available online 3 September 2012

Abstract

Objective. – Most of the studies about trapeziometacarpal joint assume that it exhibits only two independent degrees of freedom, but the experimental or theoretical support for considering a two-degrees of freedom model is not always clear.

Materials and methods. – Therefore, an in vitro kinematic study has been designed to demonstrate, from experimental data, that only two of the trapeziometacarpal degrees of freedom (i.e., flexion/extension and adduction/abduction) are non-null and independent. Several movements of maximal amplitude in flexion, abduction and circumduction have been realized and the relative position and orientation of the segment coordinate system embedded on the first metacarpal with respect to that embedded on the trapezium have been collected using electromagnetic sensors. The trapeziometacarpal rotations have been described using a joint coordinate system and the joint displacements have been evaluated on the axes of this coordinate system.

Results. – The root mean square (RMS) values of the joint displacement components have been found small enough to assume that the trapeziometacarpal joint has no translation degrees of freedom. A paraboloid coupling equation has been found between the internal/external rotation angle and the two other, flexion/extension and adduction/abduction, angles.

Conclusion. – Thus, this study demonstrates that the trapeziometacarpal joint has only two independent rotational degrees of freedom, and further, the described methodology could also be used to determine the coupling laws between degrees of freedom of various joints.

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Résumé

Objectif. – La plupart des études sur l’articulation trapézo-métacarpienne considèrent que cette articulation présente seulement deux degrés de liberté indépendants, mais les données expérimentales ou théoriques sur lesquelles se fonde cette hypothèse ne sont pas toujours clairs.

Matériels et méthodes. – Aussi, une étude cinématique in vitro a été mise en place pour démontrer, à partir de données expérimentales, que seuls deux des degrés de liberté de l’articulation trapézo-métacarpienne (i.e., flexion/extension et adduction/abduction) sont non nuls et indépendants. Plusieurs mouvements d’amplitude maximale en flexion/extension, adduction/abduction et circumduction ont été réalisés et la position et l’orientation relatives du repère segmentaire lié au premier métacarpien par rapport à celui lié au trapèze ont été enregistrées par des capteurs électromagnétiques. Les rotations de la trapézo-métacarpienne ont été décrites selon les axes d’un repère articulaire et les déplacements articulaires ont été évalués sur les mêmes axes.

Résultats. – Les valeurs RMS des déplacements articulaires ont été trouvés suffisamment faibles pour considérer que l’articulation trapézo-métacarpienne ne possède pas de degrés de liberté en translation. Une équation de couplage paraboloïde a été définie entre l’angle de rotation interne/externe et les deux autres angles de flexion/extension et adduction/abduction.

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1. Introduction

The complex function of the thumb, including pure motions of flexion and adduction, and composite motions of opposition and circumduction, is the result of the specific anatomical structures of the trapeziometacarpal (TMC) joint: articular surfaces and ligaments.

From an anatomical point of view, the surfaces in contact in the TMC joint are generally described as saddle shaped surfaces or condylar [1–3]. However, it is impossible to determine the degrees of freedom (DoFs) of the TMC joint from the description of the contact surfaces only. Mechanically, in saddle shaped and condylar joints, no surface but linear or punctual contact exists, the number of DoF is four to five, except if they are assumed as portions of a torus [4]. In this case, the surfaces would be revolute and the joint would have only one DoF (about the symmetry axis of the torus). Clinically, as for the other joints, the DoFs of the TMC joint rely on the important role played by the muscles and passive structures [1,3,5–7], which have been highlighted in a recent review on the TMC anatomy [8]. A kinematic approach, either in vitro or in vivo, is therefore required.

Most of the studies about the TMC joint kinematics [2,9–11] considered that this joint has two independent DoFs: flexion/extension about an axis embedded on the trapezium and adduction/abduction about an axis embedded on the first metacarpal. It is also admitted that both axes are not perpendicular and non-intersecting [11–13]. However, the experimental or theoretical support for considering such two-DoF model is not always clear. For instance, the amount of internal/external rotation reported in some studies [2,14–16] may appear somewhat confusing if it is not considered as a coupled DoF.

Actually, the correct definition of the functional rotation axes, i.e. the axes around which the joint can realize “pure” movements, without any combined movement around another axis, is of major importance. Indeed, when a given joint has only two independent DoFs, the reporting of the joint rotations on a Joint Coordinate System (JCS) based on these two axes would show no range of motion around the “floating” axis, whatever the movement realized, whereas the reporting of the joint rotations for the same movement using an ill-defined Segment Coordinate System (SCS) or JCS would lead to angular variations on the three axes, known as a “cross-talk”. The influence of the determination of the correct direction of the rotation axes has been shown, for example, on the knee joint [17].

The purpose of this study was to experimentally determine the number of DoFs of the TMC joint from an in vitro kinematic analysis. However, rather than a priori assuming a two-DoF kinematic model, the choice has been to keep the three open cylinder chain description of the JCS [18–20] and to characterise all the six rotational and translational DoFs. The hypothesis of this work was that it could be demonstrated that only two of the DoFs (i.e., flexion/extension and adduction/abduction) are not negligible and independent.

2. Materials and methods

2.1. Experimental protocol

A fresh-frozen right hand specimen of an asymptomatic subject (female, 76-years-old) has been used after a 24 hours defrosting period at ambient temperature. The hand was disarticulated 30 cm proximal to the wrist joint. All the structures (the joint capsules, the ligaments and the muscular insertions) were kept intact, except at the disarticulation level, in order to maintain joint congruence.

The first step consisted in the TMC movement recording. The specimen was fixed by non-ferromagnetic pins drilled through the forearm, the lunate and the scaphoid on a wooden board. An intra-cortical non-ferromagnetic pin was implanted in the first metacarpal, this pin being equipped with a sliding-hinge joint, allowing the operator to move passively the first metacarpal without imparting any axial rotation (Fig. 1). Two Flock of Bird (FoB, Ascension Technology Corp.) electromagnetic sensors (5 × 5 × 10 mm) were firmly fixed on two non-ferro-magnetic holders screwed in the trapezium and the first metacarpal, respectively. The errors of this electromagnetic tracking device have been found less than 2% [21]. The holders were designed in such a way that they could be screwed in the bone without limiting normal joint motion. Moreover, both FoB sensors could be easily assembled and disassembled on the holders. The 3D locations of the two FoB sensors (i.e., technical trapeziun and first metacarpal coordinate systems) were simultaneously collected in the inertial coordinate system (i.e., the laboratory reference frame), with a sampling rate of 100 Hz.

Several TMC movements (at relatively slow speed and with maximal passive amplitude) were carried out by the operator and collected:

![Fig. 1. Overview of the experimental set-up.](image-url)
six movements of flexion/extension;
- six movements of adduction/abduction;
- six movements of circumduction.

The flexion/extension movement was performed by taking the thumb roughly perpendicular to the plane of the hand palm, and the adduction/abduction movement was performed in the plane of the hand palm.

The second step, after joint opening, consisted in a calibration procedure performed by a clinician experimented in hand surgery. One FoB sensor was kept screwed in the trapezium. The other FoB sensor was fixed on a pointer (with pre-calibrated extremity) in order to point classical anatomical landmarks [2,22]. Then, the procedure was opposite in order to point the anatomical landmarks of the first metacarpal (Fig. 2).

This calibration step allowed defining the coordinates of the anatomical landmarks in the technical trapezium and first metacarpal coordinate systems.

2.2. Anatomical coordinate system construction

The axes of the anatomical coordinate systems embedded on the trapezium and the first metacarpal are defined according to [23] and [16], (Fig. 2).

For the trapezium, the $Z_t$ axis is the unit vector of the line joining the TM2 J (trapezium - second metacarpal joint centre) to the TDET (tubercle distal end). The $X_t$ axis is built in a dorsal-volar direction as the cross-product between the axis extending from the TM1 J (trapezium - first metacarpal joint centre, i.e., mid-point of the central ridge of saddle) to the TSTJ (trapezium - scaphoid - trapezoid junction centre) and $Z_t$. At last, $Y_t$ is built by the cross-product between $Z_t$ and $X_t$, running in a distal-proximal direction.

For the first metacarpal, the $Y_m$ axis is defined as the line from the metacarpal base centre (MBC) to the mid-point between metacarpal medial distal tubercles (MMDT) and medial and lateral distal tubercles (MLDT). $X_m$ is then defined as the cross-product between a vector joining the distal tubercle (MMDT and MLDT) and $Y_m$, running in a dorsal-volar direction. At last, $Z_m$ is built as the cross-product between $X_m$ and $Y_m$ and runs so in a medial-lateral direction.

Both origins ($O_t$ and $O_m$) are assumed coinciding with the mean functional joint centre of rotation, evaluated by SCoRE method [24] using all circumduction movements. The mean centre of rotation is then assumed rigidly fixed in the trapezium SCS (to define $O_t$), and rigidly fixed in the first metacarpal SCS (to define $O_m$).

2.3. Joint coordinate system definition and degree of freedom assessment

The TMC rotations are described using a JCS, according to [23] and [16]: $\theta_1$ flexion (+)/extension (–) about $Z_t$, $\theta_2$ internal (+)/external (–) rotation about the floating axis $Y_f$ and $\theta_3$ adduction (retroposition) (+)/abduction (anteposition) (–) about $X_m$.

The joint displacements (from the origin of the trapezium anatomical coordinate system $O_t$ to the origin of the first metacarpal anatomical coordinate system $O_m$) are evaluated on the JCS axes using a non orthogonal projection [25,26]: $d_1$ medial (+)/lateral (–) about $Z_t$, $d_2$ proximal (+)/distal (–) about the floating axis $Y_f$ and $d_3$ anterior (+)/posterior (–) about $X_m$.

The root mean square (RMS) and maximum values of the joint displacement components are computed for all the collected movements. Besides, to point out the coupling relationship between the internal/external rotation $\theta_2$ and the two other joint angles, the surface drawn by the successive joint orientations in the ($\theta_1$, $\theta_2$, $\theta_3$) space for four among the six movements of flexion/extension, adduction/abduction and circumduction is fitted with the equation of a paraboloid surface. Actually, the relationship is obviously non linear, and among the quartic surfaces, the paraboloid surface has the advantage to give a unique solution for the regression equation. In the paraboloid coordinate system (denoted $p$), the coupling equation is given by:

$$\left(\theta_{p}^*\right)^2 = \frac{\left(\theta_{1}^p\right)^2}{a^2} + \frac{\left(\theta_{2}^p\right)^2}{b^2}$$

Then, the evaluation of the fitting with this paraboloid surface is tested on the two other movements of each type by computing the root mean square error (RMSE).

3. Results

3.1. Quantification of joint displacements

On the total of $n = 1153$ frames, the three joint displacements are:

- $d_1$: RMS = 1.7 mm, maximum 4.9 mm;
- $d_2$: RMS = 2.0 mm, maximum 5.9 mm;
- $d_3$: RMS = 3.0 mm, maximum 6.3 mm.

These values are small enough to assume that the TMC joint has no translation DoF.

3.2. Coupling equation between joint angles

Fig. 3a shows the surface drawn by the successive joint orientations in the ($\theta_1$, $\theta_2$, $\theta_3$) space for all movements. The cian lines correspond to the flexion/extension movement, the magenta lines correspond to the adduction/abduction movement, and the green lines correspond to the circumduction movement. The movement amplitudes are in the range $[-14^\circ,40^\circ]$ for $\theta_1$, $[-24^\circ,47^\circ]$ for $\theta_2$, and $[-24^\circ,36^\circ]$ for $\theta_3$. Fig. 3b shows the paraboloid fitting. The blue points correspond to the set of angles used to fit the paraboloid surface and the red points correspond to the set of angles used to evaluate this fitting.

The coefficients of the coupling equation were $a = 0.2013$ and $b = 0.0946$.

The paraboloid coordinate system being defined, in the ($\theta_1$, $\theta_2$, $\theta_3$) space, by:
Fig. 2. Landmarks used to define both the anatomical coordinate systems embedded on the trapezium and the first metacarpal, trapezium and first metacarpal anatomical coordinate systems, schematic representation of the joint coordinate system.

Fig. 3. a: representation of the trapeziometacarpal (TMC) movements in the \((θ_1, θ_2, θ_3)\) space (cyan lines for the flexion/extension movement, magenta lines for the adduction/abduction movement, and green lines for the circumduction movement); b: fitting of the three angles by a paraboloid surface (blue points for the set of angles used to fit the paraboloid surface and red points for the set of angles used to evaluate this fitting).
• origin $\mathbf{O}^p = [-5.2723, -12.4225, 17.6543]^T$ (in degrees)
• axis $\mathbf{i}^p = [0.7554, -0.4465, 0.4796]^T$
• axis $\mathbf{j}^p = [-0.2589, 0.4689, -0.8444]^T$
• axis $\mathbf{k}^p = [0.6020, 0.7621, 0.2386]^T$

The fitting error $\theta_p^\ast - (\theta_p^p)^\ast$ is $\text{RMSE} = 2.56^\circ$, maximum $8.63^\circ$ on $n = 713$ points, and the evaluation error $\theta_2^p - (\theta_2^p)^\ast$ is $\text{RMSE} = 2.76^\circ$, maximum $8.91^\circ$ on $n = 440$ points.

4. Discussion

The determination of the DoFs of the human joints is an open topic. For instance, the ankle, shoulder and knee joints have been specifically studied [27–29]. The number of independent DoFs (and the coupled DoFs) has been generally determined experimentally and 3D kinematical models or coupling equations have been proposed [30,31]. In vitro, kinematic analysis is generally preferred because the function of each ligament can be assessed individually [10,32] and because bone pins allow precise measurement of the joint mobility. Especially for the TMC joint, an in vivo kinematic analysis with skin-based markers is difficult to perform [33–35]. Therefore, medical imaging methods have been used but provide only pseudo-kinematics (i.e., limited number of successive static postures) [12,16] except with fluoroscopy [34].

Based on an in vitro kinematic analysis, the results of the present work are consistent with most of the past studies about the TMC joint kinematics [2,10,13], which considered that this joint has two independent DoFs: flexion/extension and adduction/abduction. For most of the authors, the observed internal/external rotation is mechanically coupled with the two other DoFs. Our results, without assuming any kinematic model, tend to demonstrate this. Actually, the fitting and evaluation errors are small enough to assume a coupling: the TMC joint has therefore two independent rotational DoFs (i.e., flexion/extension and adduction/abduction), the other rotational DoF (i.e., internal/external rotation) being coupled with them.

The patterns of TMC movements in the $(\theta_1, \theta_2, \theta_3)$ space and the ranges of motion obtained in this study are coherent with the data given in literature (e.g., [2,15,33,36]).

Moreover, the present study states an example of coupling equation giving the possibility to assess the internal/external rotation value for a given set of flexion/extension and adduction/abduction angles.

The significance of these results is limited, and especially the value of the coefficients of the coupling equation fitting the paraboloid shape, as only one hand has been tested. These coefficients are also specific to the used JCS. Moreover, the reported limited number of DoFs for the TMC joint results not only from the articular contacts and the ligament restraints but also from the role of muscles, tendons and other soft tissues. All these structures are modified in an in vitro study. However, this study describes an approach suitable to define the coupling laws between joints’ DoFs. The same methodology can be used, either in vivo or in vitro, for any other human joint for which the number of DoFs is limited and the functional axes are difficult to assess, for example the ankle or knee joints [11,37–39].

Acknowledgements

The authors would like to thank J.C. Assion and P. Dupire for their technical help in the experiments. The hand specimen was obtained from the laboratoire d’anatomie de la faculté de médecine Lyon-Est (Pr. J. Bejui-Hugues), Lyon, France.

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