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TITLE: Validity of a simple videogrammetric method to measure the movement of all hand segments for clinical purposes

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Abstract

Hand movement measurement is important in clinical, ergonomics and biomechanical fields. Videogrammetric techniques allow the measurement of hand movement without interfering the natural hand behaviour. However, an accurate measurement of the hand movement requires the use of a high number of markers, which limits its applicability for the clinical practice (60 markers would be needed for hand and wrist). In this work, a simple method that uses a reduced number of markers (29), based on a simplified kinematic model of the hand, is proposed and evaluated. A set of experiments has been performed to evaluate the errors associated to the kinematic simplification, together with the evaluation of its accuracy, repeatability and reproducibility. The global error attributed to the kinematic simplification was 6.68°. The method has small errors in repeatability and reproducibility (3.43° and 4.23°, respectively) and shows no statistically significant difference with the use of electronic goniometers. The relevance of the work lies in the ability of measuring all degrees of freedom of the hand with a reduced number of markers without interfering the natural hand behaviour, which makes it suitable for its use in clinical applications, as well as for ergonomic and biomechanical purposes.

Keywords

3D movement, accuracy, hand joint angles, hand posture, reflective markers, repeatability, reproducibility.

Introduction

The hand has a great number of bones connected through different joints that allow 25 degrees of freedom (DoFs) approximately. Its movement is usually described in clinical and biomechanical fields by means of a set of physiological joint rotation angles (PJRAs): flexion/extension (F/E), abduction/adduction (Ab/Ad) and pronation/supination (P/S). As described by Brand and Hollister,[1] it is usual to consider only one DoFs at all the interphalangeal (IP) joints, corresponding to a F/E rotation. Metacarpophalangeal (MCP) joints are usually considered as two DoFs joints, corresponding to F/E and Ab/Ad rotations, as only a slight passive P/S rotation is allowed. The movement of the carpometacarpal (CMC) joints is more complex, combining F/E, Ab/Ad and P/S rotations. Anyway, the thumb CMC joint acts mainly with two predominant DoFs, so that commonly only F/E and Ab/Ad rotations are considered; no movement at all is usually considered at index and middle CMC joints, whereas the movements at the ring and little CMC joints, of small amplitude, are usually referred as F/E rotations.

Hand movement measurement is required in many fields, as in the functional evaluation for pathological diagnosis, the follow-up evaluation of rehabilitation, the analysis of sportive techniques or the ergonomic evaluation of handheld tools use. Different techniques have been used in the past to measure hand movement, such as goniometers, instrumented gloves or motion tracking from digital images.[2-6] Many of these techniques do not allow for the simultaneous measurement of all DoFs or do not use the PJRAs to express the angles. Furthermore, it is usually desirable that the measuring technique does not interfere with the normal development of the hand activities. In this sense, the motion tracking of passive markers from video images (videogrammetry) is a good choice,[3,7] as although some movement restriction can be introduced by using passive markers, it is much lower than using instrumented gloves or electronic goniometers. It has been widely used in gait analysis, but its application to the hand movement analysis is still scarce.[8] Most works in the literature present its use only for one finger,[9-11] or they consider important kinematical simplifications,[12-14] especially in describing the kinematics of the thumb and in considering the palm as a rigid body. In recent works, Cerveri et al.[15] and Chang and Pollard[16] presented a method for the accurate measurement of the thumb CMC joint taking into account the real orientation and location of the F/E and Ab/Ad rotation axes. However, this accurate measurement for the whole hand movement would require the use of a high number of markers, which limits its applicability for the clinical practice (60 markers would be needed for hand and wrist). In this work, a simple method that uses a reduced number of markers (29), based on a simplified kinematic model of the hand, is proposed and evaluated. Although some clinical and research groups have used similar methods, the method described in this paper differs not only in the number of points used, but also in its completeness regarding the physiological angles measured. Furthermore, it provides detailed information about the repeatability, reproducibility and accuracy. Thus, we emphasize that the method described in the paper allows for the measurement of all hand movements, and that the method is repeatable, reproducible and has an acceptable (and known) accuracy.

Methods

Description of the Technique

The technique consists of the placement of 29 markers on different anatomical hand landmarks; the registration of the 3D coordinates of these markers in two static reference postures (RPs) to allow the calculation of PJRAs; the registration of the 3D coordinates of these markers in any movement, and finally the PJRAs calculation.

Reference Postures. A repeatable neutral posture was used as reference, allowing the calculation of PJRAs and the comparison of measures obtained in different sessions involving complete markers removal. This RP was the combination of two postures. The first one (RP1) was used to define the neutral posture of the fingers and wrist: the forearm and hand lay on a flat surface, keeping the fingers close together and with the forearm aligned with the middle finger (Figure 1(a)). The second RP (RP2) was used to define the thumb neutral posture: the thumb was resting, with the fingers flexed and in a relaxed posture, on the lateral side of the middle phalanx of the index finger (Figure 1(b)), according to the neutral position of the CMC joint defined by Smutz et al.[17]

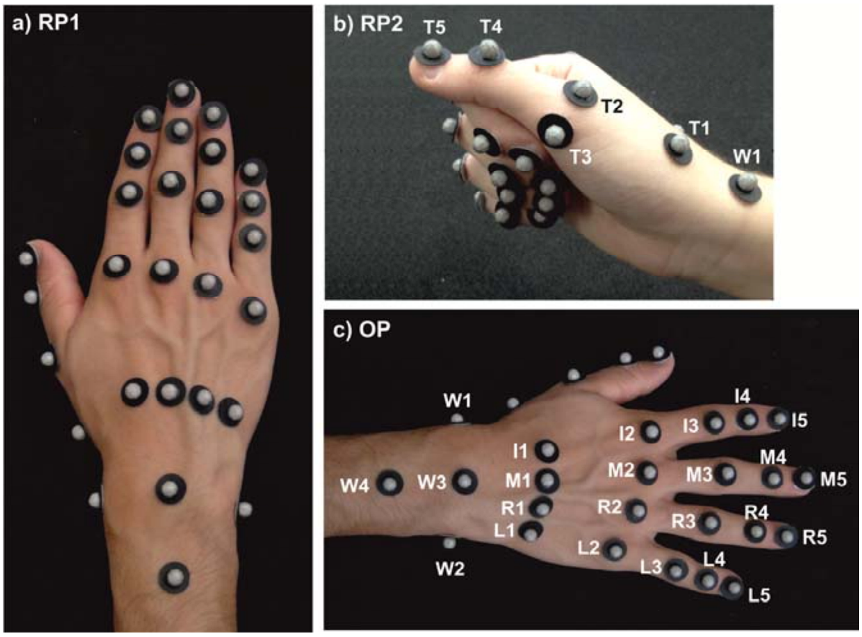

Figure 1. Postures and markers used: (a) RP1; (b) RP2 and markers for thumb (T); (c) OP and markers for index (I), middle (M), ring (R) and little (L) fingers and wrist (W).

Markers. 29 reflective markers (diameter 3 mm) were placed on the hand dorsum, to avoid hiding. From the index to little fingers (Figure 1(a)) five markers were placed as follows: first marker on the metacarpal base, second marker on the knuckle, third on the proximal interphalangeal (PIP) joint, forth on the distal interphalangeal (DIP) joint and finally, the fifth marker on the nail. Care was taken so that all markers of each finger lay on its sagittal plane when placed with the hand and forearm in the open posture (OP) defined as follows: the forearm and hand laying on a flat surface, with the phalanges and metacarpals aligned and with the forearm aligned with the middle finger (Figure 1(c)).

For the thumb, first marker was placed on the metacarpal base (T1), second and third markers (T2 and T3) on the dorsum and lateral side of the MCP joint, respectively, forth on the IP joint (T4) and the fifth marker on the nail (T5). All markers, except the third one, lay on the thumb sagittal plane when placed with the thumb in RP2 (Figure 1(b)).

Four markers were placed on the wrist, with the forearm and hand in OP (Figure 1(c)). The first and second markers were located on the radial and ulnar styloid processes (W1 and W2), respectively; and the third and forth markers (W3, W4) were placed aligned with the middle finger, on the wrist dorsum and on the forearm, keeping a distance of 2.5 cm.

Obtaining the 3D Coordinates of the Markers. The 3D coordinates of the markers were registered in both RPs and during the hand movements to be measured using a Vicon motion tracking system (Vicon®) consisting of 8 Vicon Bonita cameras. The 8 cameras were positioned enveloping the workspace at different heights, so that the markers were always visible in at least two cameras, avoiding hiding. All processing and motion capture was performed using the Nexus software (Vicon®). The system was calibrated, and the Nexus software allowed the automatic markers tracking (link-based model) and their 3D coordinates reconstruction.

Simplified kinematic model. Calculation of Physiological Angles of Rotation. To decompose the relative orientation between consecutive segments into rotations with physiological meaning, it would be necessary to know the exact position and orientation of the anatomical rotation axes. In the absence of these data, it is usual to consider the kinematic approximation that the F/E axes are perpendicular to the segments, and the F/E and Ab/Ad axes in joints with two DoFs are perpendicular between them, although this is not strictly true.[1] We used this simplification, and selected Cartesian coordinate systems with axes coincident with the rotation axes: Z axis corresponding to F/E, X axis to Ab/Ad and Y axis corresponding to P/S. As recommended by the ISB,[18,19] Y axes were defined positive in proximal direction, X axes in palmar direction and Z axes in radial direction.

The rotation angles at each joint were obtained by superposing the proximal coordinate systems of the reference and grasping postures, and calculating the rotation angles between the distal coordinate systems of the reference and grasping postures, according to the Euler convention[20] with sequence Z-X-Y-axes. The rotation angles computed that did not correspond to PJRAs were considered as residuals (Table 1).

Table 1. Simplified kinematic model. Angles measured at each joint.

Joint	Z rotation	X rotation	Y rotation
Wrist	F/E	Ab/Ad	Residual
Thumb CMC	F/E	Ab/Ad	Residual
Thumb MCP	F/E	Ab/Ad	Residual
Thumb IP	F/E	Residual	Residual
Index MCP	F/E	Ab/Ad	Residual
Index PIP	F/E	Residual	Residual
Index DIP	F/E	Residual	Residual
Middle MCP	F/E	Ab/Ad	Residual
Middle PIP	F/E	Residual	Residual
Middle DIP	F/E	Residual	Residual
Ring CMC	F/E	Residual	Residual
Ring MCP	F/E	Ab/Ad	Residual
Ring PIP	F/E	Residual	Residual
Ring DIP	F/E	Residual	Residual
Little CMC	F/E	Residual	Residual
Little MCP	F/E	Ab/Ad	Residual
Little PIP	F/E	Residual	Residual
Little DIP	F/E	Residual	Residual

Coordinate Systems. The coordinate systems were defined as follows:

- *Forearm:* Y axis was the vector pointing from the distal (W3) to the proximal (W4) forearm markers. X axis was perpendicular to the Y axis and to the vector linking the styloid processes markers (W1 and W2). The Z axis was the cross product between X and Y axes.
- *Finger Metacarpals:* Y axes were the vectors pointing from the distal to the proximal metacarpal markers. X axes for the index, ring and little fingers, were obtained by forcing the markers of the corresponding metacarpal and the marker on the knuckle of the middle finger (M2) to lay on the plane X = 0. For the metacarpal of the middle finger, the X axis was obtained by forcing the markers on the middle finger metacarpal (M1 and M2) and the marker on the

knuckle of the index finger (I2) to lay on the plane X = 0. And Z axes for the metacarpals were the cross products between X and Y axes.

- *Finger Phalanges:* Y axes were the vectors pointing from the distal to the proximal phalange markers. For the proximal phalanges of the middle, ring and little fingers, X axes were obtained considering that the corresponding markers on the phalange and the marker on the knuckle of the preceding finger lay on the plane X = 0. For the proximal phalange of the index finger, the X axis was obtained considering that markers on this phalange and the marker on the knuckle of the middle finger lay on the plane X = 0. For all middle and distal phalanges of index to little fingers, X axes were calculated considering that their Y axes and the Z axis of the corresponding proximal phalanx defined the plane X = 0. The Z axes of all phalanges were the cross products between X and Y axes.
- *Thumb:* Y axes for all segments were the vectors pointing from the distal to the proximal segment markers. For the thumb in RP2, the same plane Z = 0 was considered for all three segments, obtained by a least squares fitting of a plane containing all 4 markers aligned with the thumb (T1, T2, T4 and T5). The X axes of all segments were the cross products between Y and Z axes. To define the coordinate system of the metacarpal and proximal phalange in other postures, two auxiliary vectors were used: a vector from T1 to T3, attached to the metacarpal (Aux1), and a vector from T2 to T3, attached to the proximal phalange (Aux2). The angle between Aux1 and the metacarpal plane X = 0, and between Aux2 and the proximal phalange plane X = 0 were then calculated. These angles were used to define the orientation of the axes of the

metacarpal and proximal phalange, forcing the auxiliary vectors to keep the same angles with respect to the planes X = 0 in the new posture. For the distal phalange, the markers T2, T4 and T5 were forced to lay on the plane Z = 0, and the X axis was the cross product between Y and Z axes.

The origins of all coordinate systems were on the segment proximal marker.

Validation Experiments

Repeatability. The RPs have to be repeatable to assure the technique reliability. To assess their repeatability, the same operator placed the markers to five healthy subjects (Table 2) who were asked to repeat the RPs three times. The RPs repeatability was analysed in terms of the rotation angles required to transform the coordinate systems between adjacent segments. A global repeatability error was computed as the root mean squared error (RMSE) in an analysis of variance (ANOVA) on rotation angles between adjacent segments with factor 'subject x joint'.

Table 2. Descriptive data of subjects participating in the experiments

Subject	Sex	Age (years)	Hand length (mm)	Hand breadth (mm)
1	Male	43	192	79
2	Male	47	185	88
3	Male	24	208	89
4	Female	25	175	73
5	Female	43	170	74

The repeatability of the PJRAs obtained from the use of the technique described in section II was assessed in a test performed by the same operator to the same five subjects. First, the RPs were registered to each subject. Afterwards, the subjects, seated at a table, grasped three different objects three times, paying special attention so that each subject grasped the objects with the same static posture in the three repetitions: 1) A cone (Figure 2(a)): the subjects were asked to grasp it with the fingers always at the same cone height, although some small differences may exist; 2) A sphere (Figure 2(b)): the subjects were asked to lay their palm on the sphere and then grasp it, and raise it; 3) A cylindrical object (Figure 2(c)): the subjects were asked to grasp it with their fingers in a pinch grasp, and raise it. The objects were initially placed in the same table location in all repetitions.

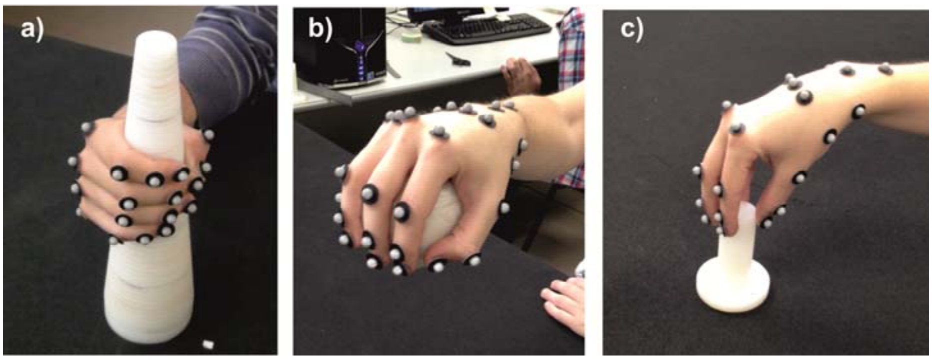

Figure 2. Grasped objects for the repeatability analysis: a) cone; b) sphere; c) cylindrical object.

In a different day, the test was repeated for all the subjects and by the same operator, with new markers. The repeatability errors of each PJRA were estimated in two ways[21]:

- *Intra-session Repeatability Error:* a global error was calculated as the RMSE of an ANOVA on the PJRAs with factor 'subject x joint x session'. This variability is associated just with the 3 repetitions of the static posture performed in each measurement, i.e. the repeatability error of the posture used. In addition, the repeatability errors for each joint were calculated from the RMSE of different ANOVAs with factor ‘subject x session’.

- *Inter-session Repeatability Error:* a global error was calculated as the RMSE of an ANOVA on the PJRAs with factor ‘subject x joint’. This variability is due to the repetition of the whole process of marker placement and the static grasping postures. In addition, the repeatability errors for each joint were calculated from the RMSE of different ANOVAs with factor ‘subject’.

Therefore the difference between both errors can be attributed just to the placement of the markers.

Reproducibility. The technique was applied by three different operators to measure the static hand posture of subjects #2 and #5 for grasping the cone. First the operator placed the markers and registered the subjects’ RPs, and afterwards the operator asked the subjects to grasp the cone three times. We assessed the effect of the operator comparing the RMSEs of two ANOVAs with PJRAs as dependent variables: the first one with factor ‘subject x joint’ and the second one with factors ‘subject x joint’ and ‘operator’. The global reproducibility error was calculated as the RMSE of the first ANOVA.

Validity and accuracy. We considered as residuals all rotation angles obtained that did not correspond to the predominant DoFs of the joints (Table 1). The absolute values of these angles at each joint give us an estimation of the error associated to the rotation axes selection in that joint. The global error attributed to the rotation axes selection was obtained as the mean value of the absolute values of all residual angles.

In addition, the reliability of the technique was analysed through the comparison with the use of standard electronic goniometers (models G35 and M110 of Penny & Giles). For subject #5, we measured the PJRAs required for the static grasp of the cone with the videogrammetric technique and with the electronic goniometers (Figure 3). It was not possible to measure all the angles of this posture simultaneously with the goniometers, and the goniometers were too big to measure the angles in DIP joints. Therefore, eight repetitions of the posture were required to achieve measuring F/E of all joints except DIP joints, and Ab/Ad of the wrist. The entire process was repeated three times. The bias between the techniques has been analysed using a pair t-test of all the simultaneous measurements.

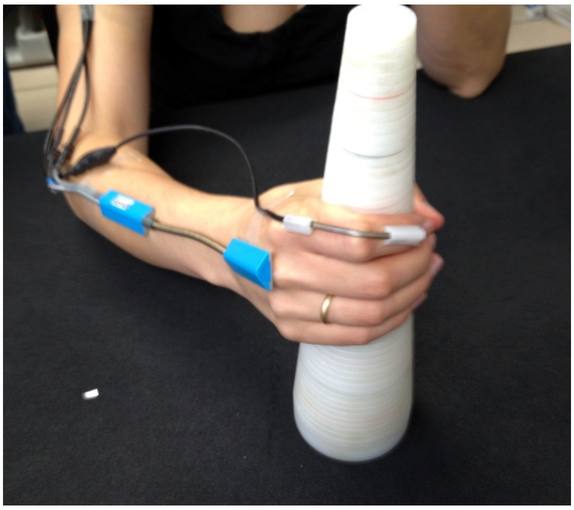

Figure 3. Hand instrumented with electronic goniometers to measure the posture while grasping the cone.

Results

Repeatability

The global repeatability error (RMSE) in the RPs measurement obtained from the corresponding ANOVA was 1.48º.

The global repeatability errors (RMSE) in the measurement of the PJRAs of the postures of grasping the cone, the sphere and the cylindrical object within the same session and in different sessions were 2.55º and 3.43º, respectively. The repeatability errors obtained separately for each object are shown in Table 3. The highest global errors were observed for the cylindrical object (2.88º and 3.79º). The errors for F/E rotation angles were slightly higher than for Ab/Ad rotation angles, and inter-session errors were somewhat bigger than intra-session errors. The highest F/E errors (3.25º and 4.22º) were observed for the cylindrical object, whereas the highest Ab/Ad errors (1.95º and 2.81º) were observed for the sphere. Table 4 shows the statistics of the errors of the PJRAs obtained with joints independently considered. Again, inter-session errors were somewhat bigger than intra-session ones. The highest errors were observed in the thumb IP F/E angles for the cylindrical object and the sphere, whereas for the cone the highest values were observed in little DIP F/E and wrist F/E angles. The highest errors for Ab/Ad angles in different sessions were observed for the thumb CMC joints (3.95º, 3.87º and 3.18º for the cone, sphere and cylindrical object, respectively). Taking into account the ranges of movement of the different joints, the mean and maximum values of relative intra-session errors were 3.01% and 9.45%, respectively; whereas the mean and maximum values of relative inter-session errors were 4.46% and 9.03%.

Table 3. Intra-session and Inter-session Repeatability Errors (RMSE). Errors have been also computed separately for F/E and Ab/Ad rotation angles.

		Within the same session	In different sessions
Cone	Global (°)	2.33	3.29
	F/E (°)	2.53	3.56
	Ab/Ad (°)	1.71	2.48
Sphere	Global (°)	2.4	3.18
	F/E (°)	2.35	3.32
	Ab/Ad (°)	1.95	2.81
Cylindrical object	Global (°)	2.88	3.79
	F/E (°)	3.25	4.22
	Ab/Ad (°)	1.61	2.32

Table 4. Statistics of the Intra-session and Inter-session Repeatability Errors (RMSE) with Joints Independently Considered.

		Cone	Sphere	Cylindrical object
Same session	Mean (°)	2.14	2.26	2.44
	Maximum (°)	5.11	4.06	8.98
	Minimum (°)	0.94	0.72	0.37
	SD (°)	0.95	0.84	1.57
Different session	Mean (°)	3.10	3.05	3.48
	Maximum (°)	5.60	4.68	8.58
	Minimum (°)	1.30	1.30	0.97
	SD (°)	1.12	0.94	1.54

Reproducibility

The RMSE calculated from the two ANOVAs performed for studying the reproducibility were 4.23° and 4.22°, the first one performed with factor 'subject x joint' and the second one with factors 'subject x joint' and 'operator'. The factor 'subject x joint' was found significant ($p = 0.000$), whereas the factor 'operator' was not ($p = 0.242$).

Validity and accuracy

The global error attributed to the rotation axes selection (mean value of all residual angles) was 6.68°, with 8.04° of standard deviation.

As expected, the correlation of the angles measured with the electronic goniometers and with this technique was high (0.981). Furthermore, no significant differences were found for them in the t-test performed (significant level >0.05), with mean and SD of differences 5.65° and 2.99°, respectively.

Finally, Figure 4 illustrates the use of the technique for the dynamic registration of the hand movement. In particular, the figure shows the evolution of the PJRAs calculated on the index finger joints during one of the cone grasping repetitions by subject #1. No filter was applied to the marker data to avoid any additional treatment that might hide the method performance. The curve profile is the expected, with the finger starting from a neutral posture, getting more flexed until grasping the cone. Also, it is possible to observe the expected correlation between flexions. It is important to remark that we did not observe any problem regarding marker hiding or in the automatic marker tracking in the analysis of any of the movements used for the validation.

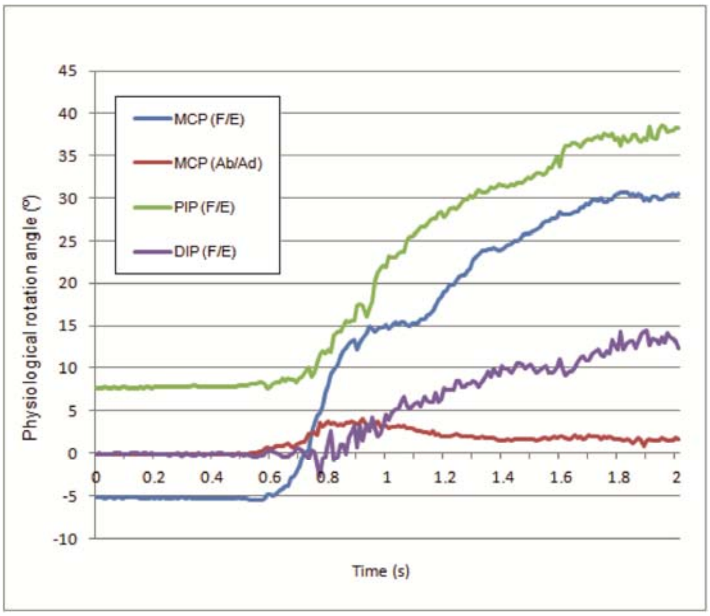

Figure 4. Evolution of the raw physiological joint rotation angles calculated on the index finger joints during one of the repetitions of grasping the cone for subject #1.

Discussion

The selected RPs were highly repeatable, with repeatability errors smaller than those reported by Carpinella et al,[12] Degeorges et al.[11] and Dipietro et al.[6] The measurement process is reliable and not affected by possible differences in the marker placement. Moreover, the technique is highly reproducible, not being dependent on the operator who performs the measurement, once instructed.

It is remarkable that the simplified kinematic model used for achieving to measure all hand DOFs with only 29 markers has been found to be a reasonable approximation. The residual angles used to assess the error attributed to the selection of the rotation axes were small. The joint rotation axes considered are, then, an acceptable approximation to the real physiological joint rotation axes taking into account that finding the location and orientation of the rotation axes would require at least three markers per segment and that the problem is highly non-linear and very time consuming, as it has been shown at the thumb CMC joint.[15]

The technique accuracy is assured from its comparison with electronic goniometers (high correlation between both techniques, and small and not statistically significant differences). The technique is, then, a good alternative to the use of electronic goniometers, less invasive and allowing the simultaneous measurement of rotation angles on all hand joints, which is not possible with the electronic goniometers.

No problems of marker hiding or automatic marker tracking were reported for the tasks analysed. However, the use of additional tracking markers may be helpful for registering more complex actions.

One of the disadvantages of using motion tracking of passive markers is that the markers location may change because of muscle contraction and skin deformation. To minimize this problem, the proposed model uses markers located on areas that are not over the hand muscles. Although most of them are located on the joints, where significant skin deformation exists, we have shown that this does not affect the accuracy of the method.

The proposed method has avoided the use of floating marker clusters used in other works,[11] so that the method is simpler and faster, and avoid collision between markers of different fingers and with the objects to be grasped. The use of such clusters is intended for gaining P/S information at the joints. However, it presents the inconvenient that some markers may occlude others from the cameras, and its convenience is discussable taking into account that the error introduced by the skin deformation is of the same order of magnitude as the P/S rotation angles occurring at the hand joints.

Compared with other existing techniques, the method proposed allows the simultaneous measurement of all DoF of the hand, using a reduced number of markers. This is not possible using goniometers, because of the space they require for their installation. Furthermore, it is also relevant that the proposed technique expresses the hand movement using the PJRAs commonly used in clinical and biomechanical fields. This is not true when using gloves, especially for the thumb CMC joint and the movement of the palm. In addition, the technique is less invasive than gloves, which add stiffness to the hand joints, affecting to the hand natural behaviour. In this sense, it is also clinically relevant that EMG data registration from the hand intrinsic muscles might be performed simultaneously to the movement measurement with the proposed technique, which is not possible using gloves; this simultaneous measurement can play an important role in the biomedical field, e.g. to provide a simultaneous characterization of the hand kinematics and EMG signals to be used in the development of control algorithms of dexterous hand prostheses. The main drawback of the technique is that the required equipment is more expensive than using goniometers or gloves. However, it is more versatile and may be easily expanded to the elbow and shoulder.

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Conflict of interest

The authors declare that there is no conflict of interest.

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