The manipulability: a new index for quantifying movement capacities of upper extremity

JACQUIER-BRET Julien, GORCE Philippe, REZZOUG Nasser

HandiBio - EA 4322 - Université du Sud, Toulon – Var, 83957 La Garde cedex, France

Corresponding Author:
Philippe Gorce,
e-mail: gorce@univ-tln.fr
Tel: +33 4 94 14 27 55
Fax: +33 4 94 14 22 78

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Abstract

In this work, it is proposed to evaluate the upper-limb movements through a global index of performance borrowed from the field of robotics: the manipulability. For a given posture, this index quantifies the set of velocities that can be achieved at the wrist in all the Cartesian directions. The manipulability can be represented by an ellipsoid from which the volume and shape related parameters can be derived. During a reach to grasp movement, the ellipsoid obtained from experiment presented a flattened shape along the forearm longitudinal axis and an increased volume as the arm was extended. From this study, it is concluded that: (1) the ellipsoid volume reflects well the ability to generate speed at the wrist which is effectively maximal for an extended posture; (2) if maximal velocity is an important parameter it might be advisable to primarily move the hand perpendicularly to the forearm longitudinal axis.

Keywords: Upper limb; biomechanics; manipulability; reach-to-grasp

Statement of relevance

The interest of manipulability indices is that they evaluate globally a posture of the upper-limb in relation to a given task. This original parameter could help to design environments or devices in order that the adopted postures maximize one particular aspect of the performance, i.e. the velocity of the hand.
1. Introduction
Reaching to and manipulating control buttons, switches, and various objects in the reachable space are common tasks executed by a human operator. Thus, the design of the workspace is of paramount importance. It must be appropriate to the task and it must place the operator in an adequate posture to make him effective. In this framework, the aim of Human Digital Modelling (HDM) is to take into account these important issues very early in the design process by means of computer simulations (Das and Sengupta 1995). These latter evaluate the reachable workspace (Chaffin 2002, Chaffin et al. 2000, Chateauroux and Wang 2008, Doriot and Wang 2006) and predict the executed movements (Chevalot and Wang 2004, Jung et al. 1995, Maurel and Thalmann 2000, Park et al. 2004, Park et al. 2006, Tolani et al. 2000, Wang 1999, Wang et al. 1998).

In the literature, the human upper limb is often modelled as a multi joint system with at least seven degrees of freedom or DOFS (Rezzoug and Gorce 2009, Tolani et al. 2000, Wang 1999, Wang et al. 1998). Positioning the hand-attached reference frame in a particular 3D configuration is a redundant task in joint coordinate space and therefore an infinite number of solutions exists. When complex movements are considered, it seems important to develop measures that reflect on the whole the implication of the DOFS. For this purpose, several indices were proposed to describe quantitatively the coordination of the DOFS. The simplest ones, the correlation coefficient (Sande de Souza et al. 2009) or the phase plots (Cirstea et al. 2003) allow to characterize the coupling between two movement parameters such as joint angles, velocities, or torques. The principal component analysis (PCA) allows to study the linear coupling of more than two DOFS during activities such as reaching or grasping (Hoffmann et al. 2006, Tseng et al. 2003). While these parameters are very useful to
characterize the coordination of the various DOFS, they do not give insight into the adequacy or the “performance” of a given posture or movement in relation to a particular task.

In the framework of robotics, such global indices are available. They are principally used to plan in an optimal way the joint trajectories of serial robots (Chiaverini et al. 2008) or of the human arm posture (Lepoutre 1993) but they have not been used to characterize the human movements. Among these indices, the manipulability (Yoshikawa 1985) seems to be specially interesting. Indeed, given a particular posture of the kinematic chain of a robot, this parameter allows to assess the set of velocities that can be achieved by the end-effector in all the Cartesian directions. This set is represented by a 3D ellipsoid from which some measures that characterize the ability to generate end-effector velocities can been identified (Mansouri and Ouali 2009). For example, in the direction of the major axis of the ellipsoid, the end-effector can move at the highest speed while the velocity is the lowest along the minor axis. Also, if the shape of the ellipsoid approaches a sphere, the end effector can evenly move in every direction.

In ergonomic applications, the assessment of this type of parameter may help to characterize the ability to produce end-effector movements effectively from a given posture. Therefore, the manipulability indices seem to be relevant to provide valuable quantitative information about some particular aspects of the “performance” of upper limb postures during upper-limb activities.

So, the aim of this study is to present and evaluate two indices derived from the ellipsoid of manipulability to assess the overall coordination of the upper limb DOFS. To this end, a classical reach-to-grasp task has been selected for its prevalence
in the interaction of human subjects with their environment and for the large number of DOFS involved during this task.

2. Material and methods

2.1. The manipulability

The human upper limb 3D configuration is modelled by a set of rigid segments linked together by joints with varying number of DOFS. The forward model $f$ maps the joint configuration $\theta$ to $x$ the 3D position of the end-effector:

$$x = f(\theta)$$  \hspace{1cm} (1)

The differentiation of this model with respect to time leads to a linear relationship between the end-effector velocity vector $\dot{x}$ and the joint velocity vector $\dot{\theta}$:

$$\dot{x} = J \dot{\theta} \text{ with } J_{ij} = \frac{\partial f_i(\theta)}{\partial \theta_j}$$  \hspace{1cm} (2)

where $J$ represents the Jacobian matrix.

For a given posture of the kinematic chain, the manipulability evaluates the capacity to generate end-effector velocities in Cartesian space from unit norm joint velocities. These latter ($\dot{\theta}$) are mapped to the end-effector velocities ($\dot{x}$) through $J$, the Jacobian matrix of size $3 \times n$, (number of DOFS) using the equation 2. Since $J$ is a linear transformation, the hyper-sphere of joint velocities (radius = 1 and dimension = $n$) is mapped to a 3D ellipsoid in the end-effector space, called the ellipsoid of manipulability. From this latter, two indices may be computed. The first one, noted $w_1$ is proportional to the volume of the ellipsoid (3). It represents the global end-effector capacity of velocity generation. The second index called $w_2$ is related to the isotropy of the ellipsoid (4) and represents the distribution of the end-effector capacity of velocity generation along each direction of the Cartesian space task. When
its value tends toward zero, the ellipsoid approaches a spherical shape, meaning that
the capability to generate a tangential velocity is similar in every direction.

\[ w_1 = \sqrt{\det(JJ^T)} \]  \hspace{1cm} (3)

\[ w_2 = \sqrt{1 - \frac{\sigma_2^2}{\sigma_1^2}} \in [0,1] \]  \hspace{1cm} (4)

In (3), \( J \) is the Jacobian matrix, \( J^T \) is the transpose matrix of \( J \), and \( \det \) is the
determinant of the product \( JJ^T \). In (4), \( \sigma_1 \) and \( \sigma_n \) represent the highest and the lowest
singular value of \( J \) respectively. They are obtained by singular value decomposition
(SVD) of \( J \).

2.2. Experimental setup

Twenty-nine healthy right-handed male subjects voluntarily participated in the
experiment which followed the recommendation of the Helsinki declaration. Before
each data collection, the protocol was explained and each subject gave his informed
consent. Then, fourteen light reflective markers were positioned on characteristic
landmarks of the trunk and the right arm according to the International Society of
Biomechanics (ISB) recommendations (Wu et al. 2005) and the subject was placed in
front of a wooden table. His legs were strapped to a standard chair to allow only the
movement of the trunk and the upper limb. Some recommendations were given to
standardize the initial upper limb posture. The back of the subject had to be supported
against the back of the chair, the hand positioned on the table with the thumb and
index joined together. The forearm rested horizontally on the support surface and had
to be in the frontal plane. This position was drawn on the table to help the subject to
adopt the same initial posture across trials. The 3D markers positions were recorded at
120 Hz by six infrared cameras (Vicon Motion Systems Inc., Oxford, UK) connected to a computer and placed in semicircle in front of the subject and on his right side.

The length of the arm was defined as being the distance between the right acromion and the midpoint between the lateral and the medial epicondyles (LE and ME respectively) of the humerus. The length of the forearm was defined as being the distance between the midpoint between LE and ME and the midpoint between the radial and the ulnar styloid processes (RS and US) respectively (see table 1 for the subjects’ characteristics).

Table 1: Mean (±SD) data of subjects (n = 29).

The task consisted in grasping an object located directly in front of the subject at a distance of 50 cm from the initial hand position. The chosen object was a 5.5-cm-diameter sphere made in polystyrene supported by a cylindrical base. The trajectories of the reflective markers were recorded during ten repetitions of the grasping task. No particular instruction was given about the duration or the movement speed. The only constraint was that the subjects were not allowed to stand up from the chair.

2.3. Data processing

Firstly, data were low-pass filtered at 6 Hz using a zero lag second-order Butterworth filter. To be compared, every trajectory was rescaled using a cubic spline resampling (101 samples): 0% of the duration corresponds to the movement onset and 100% corresponds to the instant of grasping.

Secondly, from the coordinates of the reflective markers, local coordinate frames were attached to the trunk, the clavicle-scapula, the humerus, and the forearm according to the ISB recommendations (Wu et al. 2005). Then, the rigid transformation between adjacent segments representing their relative configuration
was computed (Matlab, The Mathworks, Inc., Natick, MA, USA). Finally, 11 joint angles were calculated from the relative rotation matrices: (1) thoracic flexion-extension, (2) thoracic lateral rotation, (3) thoracic axial rotation, (4) clavicular protraction-retraction, (5) clavicular elevation-depression, (6) clavicular axial rotation, (7) glenohumeral flexion-extension, (8) glenohumeral abduction-adduction, (9) glenohumeral axial rotation, (10) elbow flexion-extension, and (11) elbow carrying angle. The axial rotation of the elbow was not considered because it has no influence on the 3D position of the wrist.

2.4. Dependent variables

Firstly, the wrist considered as the end-effector of the upper limb kinematics chain was the centre of the ellipsoid of manipulability. At each step of the normalized movement, the two manipulability indices \( w_1 \) and \( w_2 \) were calculated. In addition to the isotropy index, the length of the three principal axes of the ellipsoid of manipulability, noted \( A_1 \), \( A_2 \), and \( A_3 \), were computed. They correspond to the product of each singular value of \( J \) and the basis vectors of the ellipsoid, both obtained from SVD. \( A_1 \) represents the major axis, \( A_2 \) the medium axis, and \( A_3 \) the minor axis.

Secondly, due to the fact that the coordinate system of the ellipsoid was not aligned with that of the forearm, the three principal axes were projected into the coordinate frame of the forearm to assess the achievable velocities of the wrist in the Cartesian space. These three axes were respectively named V for the vertical direction (x-axis of the ISB forearm coordinate system), ML for the mediolateral direction (z-axis of the ISB forearm coordinate system), and AP for the anteroposterior direction according to the forearm coordinate system (y-axis of the ISB forearm coordinate system). To perform the statistical analyses, each dependent variable was computed at five particular instants characterizing a reach-to-grasp movement (de Freitas et al.)
2007): the movement onset (τ_{start} or 0% of the relative movement time), the relative time of peak acceleration (τ_{acc}), the relative time of peak velocity (τ_{vit}), the relative time of peak deceleration (τ_{dec}), and the instant of grasping (τ_{grasp} or 100% of the relative movement time).

2.5. Statistical analysis
After checking the normality of the data and the homogeneity of the variances, a one-way ANOVA for repeated-measures was performed with the within-subject factor of time (five levels). Post-hoc analyses were performed with Tukey tests. The level of significance was set at p = 0.05.

3. Results

3.1. Shape of the ellipsoid of manipulability
During the whole movement, the shape of the ellipsoid was elongated along A_1 and A_2 (Figure 1). Indeed, the length of A_3 represented about 20% of the length of A_1 and A_2 (F_{8,224}=585.26, p<0.01). The variation over time of the length of A_1, A_2, and A_3 are given in table 2. A_1 and A_2 lengths increased during the movement (increase of 51.3% and 50.3% between τ_{start} and τ_{grasp} for A_1 and A_2 respectively, p<0.05) whereas a decrease of the length of A_3 was observed between τ_{vit} and τ_{grasp} (decrease of 25.7% between these two phases, p<0.05). For A_3, no significant difference was found between the three first phases of the movement (p>0.05).

Please insert the Figure 1 about here
Figure 1: Shape of the ellipsoid of manipulability at τ_{vit} with the representation of its three principal axes.

Please insert the Table 2 about here
Table 2: Mean dimensionless length (± SD) of the three principal axes of the ellipsoid during the reach-to-grasp movement.
3.2. Ellipsoid of manipulability relative to the wrist
To evaluate the achievable velocities of the wrist in the Cartesian space, the three principal axes of the ellipsoid were projected into the coordinate frame of the forearm. Due to this projection, the length of AP, ML and V axes were lower than $A_1$ ($p<0.05$). As for $A_3$, AP axis presented the smallest length ($F_{8,224}=24.53$, $p<0.05$) during the whole movement and a decrease was noticed between $\tau_{\text{dec}}$ and $\tau_{\text{grasp}}$ (decrease of 43.4%, $p<0.05$, table 3). The length of ML increased during the second part of the movement (increase of 30.1% between $\tau_{\text{vit}}$ and $\tau_{\text{grasp}}$, $p<0.05$). An increase of V axis length was also found but only during the middle part of the movement (increase of 24.2% between $\tau_{\text{acc}}$ and $\tau_{\text{dec}}$, $p<0.05$).

Please insert the table 3 about here
Table 3: Mean dimensionless length (± SD) of the axes of the forearm coordinate system relative to the ellipsoid of manipulability during the reach-to-grasp movement.

3.3. Manipulability Indices
The statistical analyses revealed an increase of the ellipsoid volume (+63.2%) between $\tau_{\text{start}}$ and $\tau_{\text{dec}}$ ($w_j=0.25$ to $w_j=0.41$, $F_{4,112}=193.86$, $p<0.05$) with no significant difference between $\tau_{\text{dec}}$ and $\tau_{\text{grasp}}$ (Figure 2). The isotropy index presented a similar profile compared to the evolution of the ellipsoid volume ($F_{4,112}=163.07$, $p<0.05$, figure 3) except between $\tau_{\text{start}}$ and $\tau_{\text{acc}}$ where no significant difference was found ($p>0.05$). $w_2$ increased between $\tau_{\text{vit}}$ and $\tau_{\text{dec}}$ ($w_2=0.93$ to $w_2=0.97$). In addition, the values computed for $w_2$ were very close to unity during the whole movement ($0.92<w_2<0.99$).

On the left side of Figure 4, the presented posture of the upper limb model corresponds to the maximal volume of the ellipsoid ($w_j$) which occurs at about 80% of the normalized movement time. On the right side, the mean value of the joint angles can be found. At this particular posture, the trunk presented a low axial rotation.
to the right; the two other DOFS (forward and lateral flexions) presented low values (less than 6°). The humerus was slightly rotated with respect to the clavicula with a mean retraction of 28.6° and a mean elevation of 22.1°. The upper limb was principally oriented forward, with a mean shoulder flexion of 50.6° of and a mean elbow flexion of 33.3°. Shoulder abduction and medial rotation were low (less than 10°). The global range of motion of each DOF is presented in Figure 5. Flexion-extension of the shoulder (59.8±10.4°) and of the elbow (70.1±11.5°) appear as the DOFS with the greatest movement amplitude.

Please insert the Figure 2 about here
Figure 2: Mean evolution (± SD) of the volume of the ellipsoid of manipulability (dimensionless) over time.

Please insert the Figure 3 about here
Figure 3: Mean evolution (± SD) of the isotropy of the ellipsoid of manipulability (dimensionless) over time.

Please insert the Figure 4 about here
Figure 4, left panel: 3D model of the trunk and the upper limb at the instant of the maximal volume of the ellipsoid (77% of the normalized movement time). Each grey spherical structure represents a particular joint. Right panel: corresponding mean values of each joint angle at the instant of the maximal volume of the ellipsoid. All joint angles are zero in the anatomical reference posture.

Please insert the Figure 5 about here
Figure 5: Range of motion of the trunk and of the upper limb joint angles during the reach-to-grasp task.

4. Discussion
The aim of the present study was to assess the upper limb movement capabilities through the evaluation of two indices derived from the manipulability ellipsoid. Classically, these indices are used to optimize the posture of redundant robots during motion planning (Hanafusa et al. 1981, Nakamura et al. 1989, Yoshikawa 1985). For example, considering a manipulator placed on a mobile base, Nagatani et al. (2002)
determined a zone for the mobile base, called the manipulability area, within which the manipulability is maximum. Considering the upper-limb and the wrist joint center as end-effector, two manipulability indices (ellipsoid volume and isotropy) were computed during a reach to grasp movement.

Firstly, an increase of the manipulability ellipsoid volume is observed over time, from the initial posture until the instant of grasping. The capacity to generate velocity at the wrist seems to increase with the extension of the upper limb, in particular with the flexion of the shoulder and the extension of the elbow which are the two degrees of freedom with the highest movement amplitude (Figure 5). Initially, the elbow was flexed and the hand was positioned on the table with the forearm lying in the frontal plane. From this posture, the displacement of the hand toward the target principally requires an extension of the elbow combined with a flexion of the shoulder to grasp the target, with a low joint excursion for the other DOFS. As shown in the Figure 4, when the volume of the ellipsoid is maximal the forearm is extended (low elbow flexion) with a flexion of the shoulder. So, if a high level of hand mobility is sought during a task, extended postures are preferred. Secondly, the elongated shape of the ellipsoid provides more information about the way the capacities of the wrist achievable velocities are distributed along each direction of 3D space. According to the results, the velocity that can be generated at the wrist is higher along the vertical and mediolateral directions in comparison to the anteroposterior direction. Thus, from this distribution, it might be advisable to primarily move the hand in a plane perpendicular to the longitudinal axis of the forearm.

The indices of manipulability represent velocity generation capability of a model of the upper-limb. This representation seems to be convenient because it can fully evaluate a posture regarding a particular criterion. Indeed, if a task implies the
generation of high velocities in well defined directions, then the ellipsoid can immediately characterise the adopted posture regarding the objective and may give information on which choice is best suited between several postures. In conjunction with parameters relative to other aspects of the posture such as the proximity to joint limits, this representation may help to better characterize the posture for ergonomic applications. Human motricity arises from the interplay between the musculoskeletal structure and the central nervous system that plans and controls the movements. Such as suggested by (Valero-Cuevas 2009), independently from any consideration about the central nervous system control, the proposed index provides a “mechanical filter” that gives information on the performance of a posture regarding specific indices directly linked to the structure and posture of the kinematic chain. In the framework of the reach to grasp that is a common movement of a human operator in its environment, the present study has provided a first set of data in order to characterize the evolution of the chosen parameters.

This approach based on the evaluation of different indices to quantify a particular aspect of postural performance needs further development. Although it is important for the interaction with the environment, the reach-to-grasp movement is only a part of the vast capabilities of the upper limb movement. So, it would be interesting to study more specific movements involving an operator, e.g., manipulate a joystick (Oliver et al. 2007), perform telecommunication call (Lin et al. 2009), use new technologies such as touchscreen (Shin and Zhu 2011), or the impact that could have different settings of an office chair on the movements (Groenesteijn et al. 2009). Together with other measures, it may help to optimize the organization of the workspace (Wang and Trasbot 2011) or the use of technical assistance such as wheelchairs (Gorce and Louis 2011).
In the present study, the hand and the fingers were not considered. During fine manual task, the evaluation of the manipulability of the fingers can provide an interesting measure of dexterity (Hoffman et al. 2011, Rogers et al. 2008) similarly to previous studies developed in the field of robotics. Indeed, Shimoga presented eight available dexterity measures including several ones derived from the ellipsoid of manipulability (Shimoga 1996). Based on this work, the study of the human hand dexterity through the manipulability assessment could provide interesting and quantitative data about how the necessary sensorimotor functions are organized to exploit and reach the mechanical capabilities of limbs and fingers (Valero-Cuevas 2009).

Other indices derived from the manipulability analysis have special interest. Indeed, the ellipsoid of manipulability has a counterpart in the force domain called the force ellipsoid (Sasaki et al. 2011a, b, Shimoga 1996, Tanaka et al. 2006). This representation allows to describe the set of possible end-effector static forces that can be generated. The graphical representation is also an ellipsoid with the same axes as the manipulability ellipsoid but with different lengths. It appears that in the direction of maximal velocity the force that can be exerted are the lowest. Another index called the dynamic manipulability takes into account the segment limbs inertia and gives insight into the acceleration generation capability.

In conclusion, the manipulability and the associated parameters may be a relevant approach to assess quantitatively the performance of the upper limb degrees of freedom coordination from a postural point of view. This original approach can give information that can characterize the adequate postures and movements during the execution of a specific task by maximizing the performance, e.g. the velocity of the hand. In a future work, it will be interesting to associate these parameters with
studies about discomfort or with the results of studies on the risk of developing musculoskeletal disorders (MSD) (Boninger et al. 2005, Mukhopadhyay et al. 2009, Mukhopadhyay et al. 2007) in order to find the best compromise between MSD risk minimization and postural performances according to the chosen indices.
References


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Table 1: Mean (± SD) data of subjects (n = 29).

Table 2: Mean dimensionless length (± SD) of the three principal axes of the ellipsoid during the reach-to-grasp movement.

Table 3: Mean dimensionless length (± SD) of the axes of the forearm coordinate system relative to the ellipsoid of manipulability during the reach-to-grasp movement.

Figure 1: Shape of the ellipsoid of manipulability at $\tau_{vit}$ with the representation of its three principal axes.

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Figure 3: Mean evolution (± SD) of the isotropy of the ellipsoid of manipulability (dimensionless) over time.

Figure 4, left panel: 3D model of the trunk and the upper limb at the instant of the maximal volume of the ellipsoid (77% of the normalized movement time). Each grey spherical structure represents a particular joint. Right panel: corresponding mean values of each joint angle at the instant of the maximal volume of the ellipsoid. All joint angles are zero in the anatomical reference posture.

Figure 5: Range of motion of the trunk and of the upper limb joint angles during the reach-to-grasp task.
6. Full list of table and figure

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<table>
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<tbody>
<tr>
<td>Age (years)</td>
<td>26.2±5.1</td>
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<tr>
<td>Weight (kg)</td>
<td>73.2±8.8</td>
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<tr>
<td>Height (cm)</td>
<td>178.7±6.4</td>
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<tr>
<td>Arm length (cm)</td>
<td>29.2±2.8</td>
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<td>Forearm length (cm)</td>
<td>26.9±1.4</td>
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Table 2: Mean dimensionless length (± SD) of the three principal axes of the ellipsoid during the reach-to-grasp movement.

<table>
<thead>
<tr>
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<th>A1</th>
<th>A2</th>
<th>A3</th>
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<tbody>
<tr>
<td>( \tau_{\text{start}} )</td>
<td>0.91 (±0.03)(^*)</td>
<td>0.83 (±0.03)(^*)</td>
<td>0.33 (±0.01)(^*)</td>
</tr>
<tr>
<td>( \tau_{\text{acc}} )</td>
<td>0.95 (±0.03)(^*)</td>
<td>0.85 (±0.03)(^*)</td>
<td>0.34 (±0.01)(^*)</td>
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<tr>
<td>( \tau_{\text{vit}} )</td>
<td>1.10 (±0.03)(^*)</td>
<td>1.00 (±0.03)(^*)</td>
<td>0.32 (±0.01)(^*)</td>
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<tr>
<td>( \tau_{\text{dec}} )</td>
<td>1.30 (±0.03)(^*)</td>
<td>1.17 (±0.03)(^*)</td>
<td>0.27 (±0.01)(^*)</td>
</tr>
<tr>
<td>( \tau_{\text{grasp}} )</td>
<td>1.38 (±0.02)(^*)</td>
<td>1.25 (±0.02)(^*)</td>
<td>0.24 (±0.01)(^*)</td>
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\(^*\): significant difference with \( A_1 \); \(^*\): significant difference with \( A_2 \).

Table 3: Mean dimensionless length (± SD) of the axes of the forearm coordinate system relative to the ellipsoid of manipulability during the reach-to-grasp movement.

<table>
<thead>
<tr>
<th></th>
<th>V axis</th>
<th>ML axis</th>
<th>AP axis</th>
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<tbody>
<tr>
<td>( \tau_{\text{start}} )</td>
<td>0.76 (±0.05)(^*)</td>
<td>0.62 (±0.03)(^*)</td>
<td>0.38 (±0.02)(^*)</td>
</tr>
<tr>
<td>( \tau_{\text{acc}} )</td>
<td>0.79 (±0.05)(^*)</td>
<td>0.62 (±0.03)(^*)</td>
<td>0.38 (±0.02)(^*)</td>
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<tr>
<td>( \tau_{\text{vit}} )</td>
<td>0.91 (±0.06)(^*)</td>
<td>0.63 (±0.04)(^*)</td>
<td>0.37 (±0.02)(^*)</td>
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<tr>
<td>( \tau_{\text{dec}} )</td>
<td>0.98 (±0.09)(^*)</td>
<td>0.70 (±0.05)(^*)</td>
<td>0.30 (±0.02)(^*)</td>
</tr>
<tr>
<td>( \tau_{\text{grasp}} )</td>
<td>1.00 (±0.10)(^*)</td>
<td>0.81 (±0.06)(^*)</td>
<td>0.26 (±0.01)(^*)</td>
</tr>
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\(^*\): significant difference with V axis; \(^*\): significant difference with ML axis.
Figure 1: Shape of the ellipsoid of manipulability at $\tau_{\text{vit}}$ with the representation of its three principal axes in the global coordinate system.
Figure 2: Mean evolution (± SD) of the volume of the ellipsoid of manipulability (dimensionless) over time.
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