Task-relevance of Grasping-related Degrees of Freedom in Reach-to-grasp Movements

Zhi Li, Jay Ryan Roldan, Dejan Milutinović and Jacob Rosen

***Abstract*— The kinematic redundancy of the human arm enables the rotation of the arm plane about the shoulder-wrist axis, represented by a swivel angle, which is affected by hand orientation when grasping. The coordination of grasping-related degrees of freedom (GR-DOFs), including swivel angle, forearm supination, wrist flexion and radial deviation, depends on their task-relevance, which can be quantified by the ratio of a joint's active motion range to its total motion range (R-AMR). The R-AMR values are computed across the target position and orientation to compare the task-relevance of the GR-DOFs. Statistical analysis of R-AMR values at the end of reach-to-grasp movements shows that among the GR-DOFs, radial deviation is most sensitive to changes in target position, while forearm supination is most sensitive to changes in target orientation. The forearm supination and swivel angle coordinate for energy-efficiency such that the swivel angle, which adjusts the posture of the whole arm, is largely unused until the forearm supination approaches its joint limit. The results further the understanding of the human motor control system in arm motion control and may benefit the design of the control algorithm for the upper limb exoskeleton.**

I. Introduction

The kinematic redundancy of the human arm enables the the rotation of the elbow position about the shoulder-wrist axis when grasping an object in a 3-dimensional (3D) workspace. Different from arm postures in reaching movements, arm postures during reach-to-grasp movements are significantly affected by the orientation of the grasp target. As a result, motor control strategies that have successfully explained arm postures in reaching movements may not be able to address arm postures in reach-to-grasp movements. For instance, Donders' law, which is valid for reaching movements [1], is not obeyed when subjects are instructed to grasp objects [2], [3], although some control strategies for reaching movements, such as the minimization of jerk, can be extended to the task of grasping [4].

Previous work has studied the control strategy of the human motor system for reach-to-grasp movement. Research has shown that hand-arm coordination is subject to both temporal [5] and spacial constraints [6]. While approaching a target, arm movement directs the thumb, preparing to match the hand orientation with the target [4], [7]. The rotation of the arm plane about the shoulder-wrist axis is coordinated with the supination of the forearm to achieve the desired hand orientation. If the target orientation is perturbed when the hand is moving to the target, the hand orientation begins to match the original target orientation and then adjusts to match the final target orientation [8]. This smooth adaption to the perturbed target orientation implies that the reach-to-grasp movements may be a superposition of separate reaching and grasping components. Given arm postures predicted for reaching movements [9]–[20], arm postures for reach-to-grasp movements can be constructed based on grasping-related differences.

Studies on movement coordination have revealed that the human motor system prefers to minimize the intervention when redundancy in control variables exists [21], [22]. The control emphasis is placed on task-relevant variables, while task-irrelevant variables are loosely monitored for tolerable variability [23], [24]. When applied to the joint coordination of a robotic manipulator, beyond distinguishing the task-relevant and irrelevant variables, it is necessary to quantitatively evaluate the task-relevance of different DOFs and assign control effort accordingly. As a result, this paper proposes a method to measure the task-relevance of coordinated DOFs, and analyzes joint coordination of the human arm in reach-to-grasp movements.

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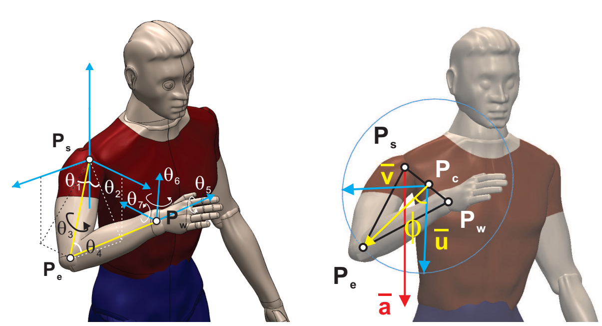
II. Methodology

A. Kinematic Modeling of Human Arm



(a) (b)

Fig. 1: The kinematic modeling of human arm: (a) seven DOFs of the human arm model; (b) the rotation of the arm plane about the shoulder-wrist axis is measured by the swivel angle ϕ.

Reach-to-grasp movements are studied based on a kinematic model of the human arm. As shown in Fig. 1, the seven degrees of freedom (DOFs) are: shoulder abduction θ_1, shoulder flexion θ_2, shoulder rotation θ_3, elbow flexion θ_4, supination θ_5, wrist flexion θ_6 and radial deviation θ_7. Due to the kinematic redundancy of human arm, the elbow position can rotate about the shoulder-wrist axis, given a fixed hand position and orientation. The amount of rotation can be measured as a swivel angle. In Fig. 1b, the direction of the swivel angle pivot axis (denoted by $\vec{n}$) is defined as:

$$\vec{n} \quad = \quad \frac{P_w - P_s}{||P_w - P_s||} \tag{1}$$

A plane orthogonal to $\vec{n}$ can be determined given the position of P_e. The point of intersection between this orthogonal plane and the vector $\overrightarrow{P_s P_w}$ is P_c. $\overrightarrow{P_c P_e}$ is the projection of the upper arm $\overrightarrow{P_s P_e}$ onto the orthogonal plane. $\vec{u}$ is the projection of a normalized reference vector $\vec{a}$ onto the orthogonal plane, which can be calculated as:

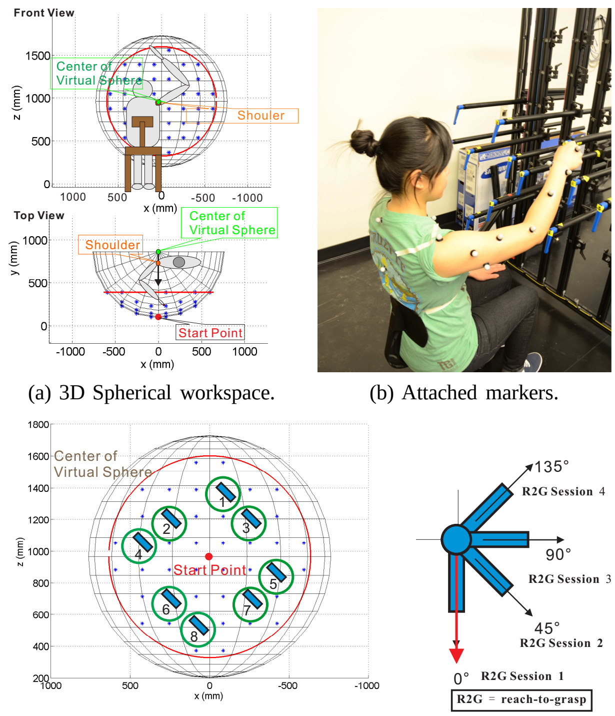
$$\vec{u} = \frac{\vec{a} - (\vec{a} \cdot \vec{n})\vec{n}}{||\vec{a} - (\vec{a} \cdot \vec{n})\vec{n}||} \tag{2}$$

The swivel angle ϕ, representing the arm posture, is defined by the angle between the vector $\overrightarrow{P_c P_e}$ and $\vec{u}$. If the reference vector $\vec{a}$ is $[0, 0, -1]^T$, then the swivel angle $\phi = 0°$ is defined when the elbow is at its lowest possible point [25]. The motion range at the elbow is limited to avoid the singularity at extreme elbow flexion and extension.

The hand paths of reach-to-grasp movements are not significantly different from reaching movements to the same target. By representing the kinematic redundancy using the swivel angle, the four grasping-related degrees of freedom are identified, namely the swivel angle and the three wrist angles. In the following sections, we will focus on the four GR-DOFs, comparing their behavior during reach-to-grasp movements with their behavior during reaching movements.

B. Experimental Protocol

The experimental protocol aimed to compare reach-to-grasp movements with reaching movements. Nine subjects (three males and six females) were instructed to conduct movements with their right arms. Each subject conducted four sessions of reach-to-grasp movements and one session of reaching movements. Each session consisted of five repetitions of eight different movements. Each subject completed a total of $5 \times 8 \times 5 = 200$ trials. During the experiment, the subjects sat in a chair with a straight back. The chair was placed such that the subject could comfortably point to each target and with his/her elbow naturally flexed. The workspace was adjusted such that the center of the workspace was aligned with the right shoulder of the subject. The subject's right arm was free for reaching movements, but the body of the subject was set against the chair back to minimize shoulder displacement. The target positions are shown in Fig. 2c. In each reaching session, after a "start" command, the subjects pointed from the start point (see Fig. 2a) to the instructed target, with their index finger in line with the forearm. In the reach-to-grasp sessions, the subjects started by pointing to the start point and reached to grasp the handle at the instructed target, the orientation of which varied in the plane that the subjects faced (see Fig. 2d). The subjects were asked to grasp the target with a firm power grasp. As shown in Fig. 2b, passive reflective markers were attached to the torso and the right arm of the subjects. A motion capture system recorded the movement at 100 Hz. To avoid fatigue, subjects took a rest after each session.



(a) 3D Spherical workspace. (b) Attached markers.

(c) Targets positions. (d) Target orientations.

Fig. 2: Experimental setup: (a) the right shoulder of the subject is aligned with the center of the spherical workspace; (b) markers are attached to the right arm and the torso for position tracking; (c) eight targets are involved in the reach-to-grasp experiment; (d) in the four reach-to-grasp sessions, the handles are oriented at $0°$, $45°$, $90°$, $135°$ on the plane that the subject face to, with respect to the direction of gravity.

C. Data Normalization and Component Separation

Based on the recorded the trajectories of the markers, the trajectories of the four grasping-related degrees of freedom (GR-DOFs) were computed by inverse kinematics. These trajectories were normalized relative to the percentage of the path length traversed by the hand (instead of time) and averaged based on five repetitions of the same movement. With reference to the reaching movements, grasping-related differences are computed so that the reaching component can be separated from the grasping component. This component separation is applied to the four GR-DOFs, including the swivel angle and the three wrist DOFs.

D. Quantification of Task-relevance

To quantify the task-relevance of each GR-DOF, the **ratio of the active motion range** (R-AMR) for each GR-DOF was computed. At a specific percentage of the hand path length, we computed the standard deviation of the value of each GR-DOF across different movements. The R-AMR at a this percentage of the hand path is then the ratio between this standard deviation and half of the motion range of this GR-DOF. Note that the R-AMR can be computed across different movement sets, including movements to targets at a particular position or in a particular orientation. For a movement set, a large R-AMR value indicates that that particular DOF is sensitive to the task parameters that vary within that movement set. For example, the R-AMR of a DOF across reach-to-grasp movements towards a particular target position with different orientations indicates the sensitivity of that DOF to target orientation. Likewise, the R-AMR of a DOF across movements to different targets that share the same orientation indicates sensitivity to target position. These across-target-orientation and across-target-position R-AMR values were computed and multiple comparison were applied to analyze the task-relevance of each GR-DOF.

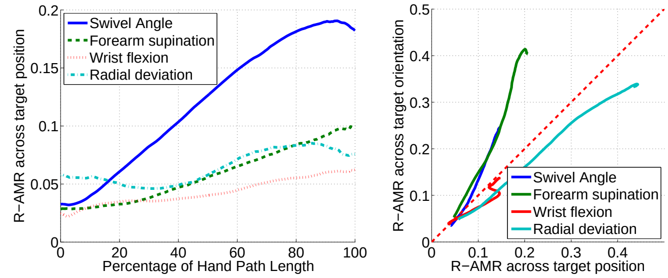
III. Results

A. *The Task-relevance During the Movements*

This section presents the results of the statistical analysis on the R-AMR values during reach-to-grasp movements. Foremost, different GR-DOFs are not used to the same extent: although arm postures start to match the target orientation early in a movement, the wrist joint, which is responsible for final adjustment, is not actively used until the hand is close to the target. As the use of a GR-DOF increases during a reach-to-grasp movement, its variance (with respect to task parameters such as target position and orientation) increases accordingly, reflected in an increased R-AMR value. To investigate task-relevance during movement, the R-AMR values were computed with increment of 0.5% of the hand path. For reaching components, R-AMR values are computed based on the standard deviations across different target positions. Fig. 3a shows the mean R-AMR values of the reaching component during movement. The mean R-AMR of the swivel angle quickly becomes much larger than that of the other DOFs. For the grasping component, R-AMR values are computed based on the standard deviation across target position and across target orientation, respectively. Fig. 3 plots the mean of the across-target-orientation R-AMR against the mean of the across-target-position R-AMR. Comparing the slopes of the four profiles, the slopes of the swivel angle and forearm supination are greater than one while the other GR-DOFs are less than one. This implies that the swivel angle and forearm supination are more sensitive to changes in target orientation than to changes in target position, while the other GR-DOFs are the opposite. It is notable that the profile for wrist flexion is nonlinear, corresponding to the opening and closing of the hand during movement in preparation for grasping the target, while for the other three GR-DOFs, the across-target-orientation R-AMR increases roughly linearly with the across-target-position R-AMR. Note also that wrist flexion near the end of the task falls on the reference line indicating equal sensitivity to both target position and orientation.

B. *The Task-relevance at the End of the Movements*

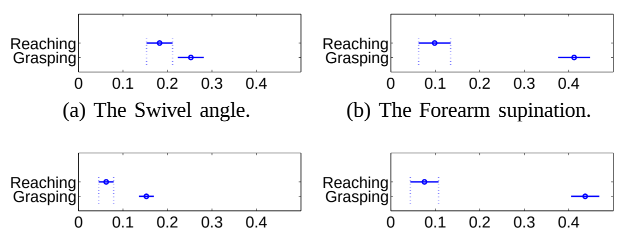
The $\text{R-AMR}_{100\%}$ value for a set of movements is the R-AMR computed at the end of the task. Fig. 4 computes $\text{R-AMR}_{100\%}$ values for reaching and grasping components separately for each subject, and compares them using multiple comparison. For all of the GR-DOFs, the $\text{R-AMR}_{100\%}$ of the grasping component is significantly larger than that of the reaching component. The swivel angle, which has the largest



(a) The reaching Component. (b) The grasping Component.

Fig. 3: The normalized R-ARM values across target position and orientation. (a) The mean R-AMR of the reaching component w.r.t the percentage of the path length; (b) the progression of R-AMR values of the grasping component during movement: across-target-position vs. across-target-orientation R-AMR for each GR-DOF starting from the bottom-left.

reaching-component $\text{R-AMR}_{100\%}$, exhibits the smallest difference between the reaching and grasping components. Among the grasping components, the forearm supination and radial deviation are much higher than the other two GR-DOFs. The wrist flexion has the lowest $\text{R-AMR}_{100\%}$ for both the reaching and grasping components, which coincides with its limited motion due to the wrist tension in power grasps.



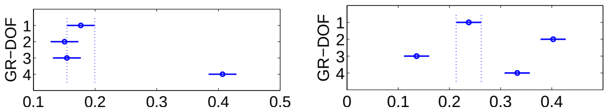
(a) The Swivel angle. (b) The Forearm supination.

(c) The Wrist flexion. (d) The Radial deviation.

Fig. 4: Multiple comparison of the R-AMR values at the end of the movements (i.e., the $\text{R-AMR}_{100\%}$) between the reaching and grasping components.

In Fig. 5, across-target-position and across-target-orientation $\text{R-AMR}_{100\%}$ values are computed without component separation. In Fig. 5a, the radial deviation has significantly higher $\text{R-AMR}_{100\%}$ across the target positions than other GR-DOFs, which implies high task-relevance to the changes in target position. Fig. 5b shows that forearm supination is the GR-DOF most relevant to changes in target orientation, while wrist flexion is least relevant. The swivel angle, which adjusts hand orientation by moving the whole arm, has much lower task-relevance than forearm supination.

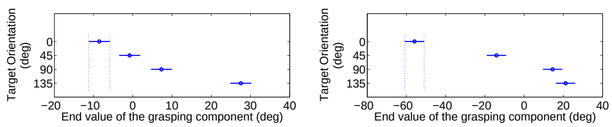
Fig. 6 compares the swivel angle and the forearm supination by their end values and across-target-position grasping-component $\text{R-AMR}_{100\%}$ values at different target orientations. Comparing Fig. 6a and 6b, the end values of the swivel angle increase significantly when the target orientation changes from $90°$ to $135°$, while the changes in the forearm supination is small. Before the target orientation reaches $90°$, the forearm supination changes more with the target orientation than the swivel angle. Comparing Fig. 6c and 6d,



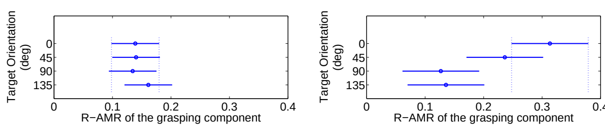
(a) Across target position. (b) Across target orientation.

Fig. 5: Multiple comparison of R-AMR$_{100\%}$ values for reach-to-grasp tasks. GR-DOFs 1 to 4 refer to swivel angle, forearm supination, wrist flexion, and radial deviation respectively.

the R-AMR$_{100\%}$ values of the swivel angle are consistently low for different target orientations, while the R-AMR$_{100\%}$ of the forearm supination is significantly reduced as the target orientation increases and settles down when the target orientation reaches $90°$.



(a) The swivel angle. (b) The forearm supination.



(c) The swivel angle. (d) The forearm supination.

Fig. 6: Multiple comparison of across-target-position R-AMR$_{100\%}$ values among different target orientations.

IV. CONCLUSION

In reach-to-grasp movements, arm posture is significantly affected by the grasp orientation. By representing kinematic redundancy using swivel angles, the grasping-related degrees of freedom, i.e., the GR-DOFs, are identified. To study the regulation effort of different GR-DOFs during reach-to-grasp movement, the ratio of active motion range (R-AMR) values to measure task-relevance was computed. For the reaching component of a movement, the swivel angle is the most task-relevant GR-DOF. For the grasping component, forearm supination and radial deviation are the most relevant GR-DOFs. For all the GR-DOFs, the grasping components are more task-relevant than the reaching components.

Within the grasping component, forearm supination and swivel angle are more sensitive to target orientation than to target position, while the other GR-DOFs are more task-relevant to target position. Comparison between the grasping components of the swivel angle and the forearm supination shows that the forearm supination is more task-relevant than the the swivel angle when the target orientations are under $90°$. This makes sense because the swivel angle adjusts the hand orientation by changing the arm posture, which tends to cost more energy. As a result, it is not highly task relevant until the forearm supination is close to its joint limit.

The task-relevance of a DOF indicates the control effort demanded by that DOF, because a DOF with high task-relevance must be responsive to task parameters. The results can be applied to further understanding of the human motor control system and formulating the inverse kinematics of the redundant human arm, a formulation that may assist in developing control algorithm for the upper limb exoskeleton.

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