HIGHLIGHTED TOPIC | Neural Control of Movement

Simultaneous control of hand displacements and rotations in orientation-matching experiments

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Torres, Elizabeth B., and David Zipser. Simultaneous control of hand displacements and rotations in orientation-matching experiments. J Appl Physiol 96: 1978–1987, 2004. First published December 19, 2003; 10.1152/japplphysiol.00872.2003.—In reach-to-grasp movements, the interaction between the hand changes in position and those in orientation is poorly understood. A theoretical approach previously proposed (Torres EB and Zipser D. J Neurophysiol 88: 1–13, 2002) assumes that motion strategies are resolved in space independently from the temporal dynamics of the motion and predicts the coarticulation of the hand transport and rotation along the path. The model implies that this simultaneous control is independent of variations in speed and initial posture and required matching orientation. This paper presents experimental data from human subjects that confirm the model’s predictions in the context of realistic, unconstrained, orientation-matching motions. Speed independence is quantified in the similarity of the postural and endpoint position-orientation paths obtained under three different speeds. Significant differences in hand and joint kinematics are shown in response to changes in initial posture and target orientation. The robustness of coarticulation under all three experimental conditions supports the idea of an intermediate stage that resolves the geometry of the motion independent of its temporal dynamics.

COGNITIVELY GUIDED ACTIONS such as reach-to-grasp are computationally difficult to solve. One of the main problems is to translate sensory input into motor execution since they “speak” different languages. Sensory input is expressed in terms of an object’s location in space, orientation, shape, etc., rather than the set of postures (or muscle configurations) required to grasp it successfully. A translation is needed between these disparate representations. This translation must resolve such problems as the difference in the number of degrees of freedom (DOF) in the space where goals are specified and the space where they are resolved, and the choice of one path among the infinity of possible paths.

To address this problem, we have previously proposed (25) a geometric stage between the representation of perceived goals and the execution of movements. This geometric stage computes paths without regard to the temporal dynamics of motion. It outputs a signal containing postural information of the same kind used by the motor execution. Decoupling the geometry from the temporal dynamics of the motion enables us to simulate realistic behavior and generate testable predictions. In the context of reach-to-grasp movements, the model yields an important prediction: the coarticulation between hand transport and orientation along the path. This prediction challenges the intuitive belief that the system may control the excess DOF by a “division of labor,” whereby proximal and distal joints have independent control of the transport and orientation phases, respectively. This scenario is quite possible because, due to redundancy, changes in any of the many joint angles of the arm may result in such an independent control.

To test coarticulation, we need an experiment different from pointing and not as complex as grasping that requires a change in the orientation of the hand while transporting it to the target location. Pointing alone is insufficient to specify orientation. Grasping adds the problem of obstacle avoidance that arises toward the end of the motion when the fingers are about to come in contact with the object, which unnecessarily confounds the issues.

The need for a cleaner assessment of coarticulation is best evidenced in the seemingly contradictory results from the grasping-related experimental literature. On the one hand, previous work involving prehension motions suggests that, in reach-to-grasp movements, distal DOF, such as those spanned by the wrist, are primarily used to shape and orient the hand, whereas proximal DOF, such as those related to the shoulder and elbow, are used independently to transport the hand to the target location (2, 15, 17). On the other hand, data from humans and nonhuman primates in response to orientation matching suggest that both the orientation and the location of targets in space affect the posture of the arm as a whole (14, 22).

Present computational models of motor control cannot simulate unconstrained motions in three dimensions with redundant DOF (11, 13, 23, 26), so there is no ground for comparison in this arena, and experimental data asking the specific coarticulation question that our model raises do not exist. This motivated the design of an experimental task that requires the kind of orientation-matching movement that we are able to simulate with geometry. In addition, we systematically manipulate important movement parameters such as speed, initial arm posture, and target orientation. Under these conditions, we question the robustness of coarticulation and compare human behavior to the model predictions concerning...
postural and endpoint paths. Of special interest is the behavior of the postural paths under these conditions, because they have not been systematically studied. The data we present in this paper provide another layer of information concerning parameters that might be useful to other models of motor control, as well as to the field of robotics devoted to the modeling of arm manipulators.

Theory and background. The theoretical aspects of this particular task have been presented elsewhere (25). The cost optimized is the general notion of distance (the norm) in a nonflat (Riemannian) space $X$ defined by the goals of the task

$$\mathbf{r} = f(l_{\text{task}}) = \sum_{i=1}^{n} \sum_{j=1}^{n} g_{ij}[x_{i_{\text{target}}} - f(q)][x_{j_{\text{target}}} - f(q)]$$

The target for action determines the dimensions of the points in this space. They are defined as functions of postural-related parameters such as joint angles in $Q$ space. One of the forms that this geometric cost may adopt in reach-to-grasp with orientation matching has been described (25), but other new goal-directed behaviors have been simulated and compared with data with new related geometric costs (24). This general notion of distance defined by the task in $X$ is preserved in joint-angle space by a geometric pullback action on the metric tensor $G_{ij}^X$ of $X$ into $Q$ defined as $G_{ij}^Q = F^T G_{ij}^X F$ where $F$ is the Jacobian matrix of the $f$ map (the metric tensor is the first fundamental form, a symmetric-positive-definite matrix whose coefficients, the $g_{ij}$'s, are used in the general definition of the line element for curved spaces). Preserving the notion of the $X$ distance in $Q$ makes the differential map of the reach-to-grasp example $f \in (T_{\mathbf{x}}Q \subset R^7 \rightarrow T_{f(\mathbf{x})}X \subset R^4)$ an isometry and guarantees that the vector flows generated in both tangent spaces $T_{\mathbf{x}}Q$ and $T_{f(\mathbf{x})}X$ are locally the shortest-distance segments between the two current points. The proof of this statement is beyond the scope of this report, but its significance is that we can generate the straight line paths (the geodesics) of any task space $X$ defined by a set of goals and transfer this notion to the higher dimensional space of joint angles $Q$.

The fact that these paths are geodesics in both spaces makes them reparameterizable in time (9) and thus speed independent. This is how we propose that it is possible to learn new motions in the cognitive-strategy space before mastering the optimal temporal profiles that ballistic/automatic motions show later.

One distinction between our approach and the rest of the field is that this geometric construction enables us to identify the subspace of joint-angle space $Q$ where the motion dictated by $X$ is resolved. Thus we can isolate the DOF that are relevant to the task in question from those that are redundant. The significance of this will be highlighted later in the data from the orientation-matching motions.

Other models of path generation (11, 26) assume the system already “knows” the best path (or trajectory) before movement initiates. Movement duration is also assumed to be known (for a review, see Ref. 28). The only information needed in our approach is the target of the task and the starting configuration of the system (initial posture in the example studied here). This information autonomously generates the solution strategy. Optimal control models of the kind above may capture the nature of automatic movement, i.e., movements that have already been learned, as in ballistic reaching. In contrast, our method aims at characterizing the ability of a system to develop the spatial solution to a given task online during learning.

Unlike other models (20, 27), this one does not need any a priori information or built-in heuristics to generate a solution path. There is no need to know the final posture as in Ref. 20, nor is there a need to remember or store any information about posture space.

Another key distinction is that the proposed framework does not enforce a strict separation between kinematics and dynamics in a serial way, whereby dynamics accommodates a previously computed kinematics trajectory. Kinematics models have a time profile to resemble the bell-shaped profiles of ballistic motions. Our approach does not produce a temporal profile. Actual data show that, as the system tries to uncover a strategy in response to a new task, the speed profiles change significantly, whereas the hand paths remain similar (24). Unfortunately, most present data come from overlearned behaviors, so this fundamental feature of motor learning, which our theory predicts, goes unnoticed.

Both the kinematics and the dynamics of motion have parameter spaces with certain geometry. Some tasks emphasize kinematics goals, whereas others emphasize dynamics-related goals. What we provide is a mechanism to build geometric strategies, which translate the cognitive conceptualization of such goals into motor-like signals. We propose that this form of geometric simulation stands between perception and action.

METHODS

Apparatus and experimental design. We needed to record the position and orientation of the hand to validate the model’s predictions. This was achieved by using a Polhemus Fastrak Motion Tracking System. This system uses electromagnetic fields to determine three-dimensional position and orientation of up to four markers relative to the stationary system at an update rate of 30 Hz each. Other than the hands, we also recorded the forearm and upper arm motions. This enabled us to recover the seven joint angles used to represent postures and extend the analysis to paths in this space.

All receivers except the shoulder’s were mounted on a piece of Plexiglas and affixed to the arm with tape. The shoulder receiver located on the acromion was mounted on plastic and attached to a harness that kept it from sliding during the motions. The locations of the markers were ~5–7 cm from the corresponding joint, depending on the anatomic measurements of each subject (Fig. 1A).

The apparatus we built for these experimental sessions is shown in Fig. 1B. Each target was labeled with a number next to it and consisted of a wooden cylinder 2 cm in diameter and 18 cm in length. The orientations used were those which were comfortable to match, ranging from 0 to 90°, where 0° corresponds to the principal axis of the cylinder being horizontally oriented and 90° to the principal axis of the cylinder being vertically oriented. The principal axis and the center of mass of the targets were marked with a red stripe and a red dot, respectively. The position and orientation distances of the targets relative to the hand-starting configuration are shown in Table 1. The basic task was to match the given position and orientation of a target in front of the body. To this end, subjects held a cylinder in their right hand and displaced it to match the given target. This required the displacement and rotation of the hand toward the target describing both a position and an orientation path.

Our model predicts that the direction of movement should be decoupled from its speed. To question the consistency of behavioral data with this idea, we investigated coarticulation under different speeds. The model also predicts an effect on the resulting motion due to different initial postures or to the required orientation. We varied these parameters as well and questioned the robustness of coarticulation under these experimental conditions.

J Appl Physiol • VOL 96 • MAY 2004 • www.jap.org
Speed condition. The experimental session began with a recorded instruction indicating the target number. This command was immediately followed by a beep, which served both as a cue to remind the subjects of the desired movement duration and to indicate that at the end of the beep the motion was to begin. The length of the beep was proportional to the desired movement time: fast (100 ms), normal (400 ms), and slow (700 ms). However, subjects adjusted the duration of the movement to their own comfortable pace for each speed kind. A summary of mean movement duration is shown in Table 1. There was enough time between the recorded instruction and the beep so that subjects could become familiar with the instructions. We used six targets positioned and oriented differently, six subjects, three different speeds, and six repetitions per speed-target combination. For statistical analysis, we divided the data set for each target (108 paths per target) into three sample groups, corresponding to the three speed groups. Each sample group had 36 trajectories. Each target was analyzed independently.

Initial posture. The question of how the initial posture affects coarticulation was assessed with the same paradigm, but in this case subjects started the movement from one of two postural configurations corresponding to the same initial hand position. In one posture (normal), the subject’s upper arm was at a comfortable configuration and the palm of the hand was facing toward the left with the thumb pointing upward (Fig. 2A). In the other posture (abducted), the upper arm was abducted and the palm of the hand was facing toward the right with the thumb pointing downward (Fig. 2B). These movements

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**Table 1. Summary of distance and movement time for the speed experiment**

<table>
<thead>
<tr>
<th>Target</th>
<th>Pos dist, cm</th>
<th>Or dist, deg</th>
<th>Slow, ms</th>
<th>Normal, ms</th>
<th>Fast, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target 1</td>
<td>101.99</td>
<td>105.83</td>
<td>1,471.3 ± 74.4</td>
<td>1,037.0 ± 22.6</td>
<td>683.9 ± 18.36</td>
</tr>
<tr>
<td>Target 2</td>
<td>99.30</td>
<td>107.79</td>
<td>1,427.8 ± 73.1</td>
<td>991.7 ± 66.1</td>
<td>680.2 ± 64.7</td>
</tr>
<tr>
<td>Target 3</td>
<td>96.29</td>
<td>126.12</td>
<td>1,503.7 ± 91.8</td>
<td>1,021.3 ± 27.8</td>
<td>665.6 ± 25.8</td>
</tr>
<tr>
<td>Target 4</td>
<td>83.02</td>
<td>101.76</td>
<td>1,376.9 ± 82.9</td>
<td>925.0 ± 28.8</td>
<td>638.3 ± 24.3</td>
</tr>
<tr>
<td>Target 5</td>
<td>39.43</td>
<td>65.49</td>
<td>1,292.6 ± 94.1</td>
<td>952.8 ± 81.0</td>
<td>628.0 ± 31.7</td>
</tr>
<tr>
<td>Target 6</td>
<td>60.03</td>
<td>93.60</td>
<td>1,219.4 ± 75.8</td>
<td>854.2 ± 22.2</td>
<td>614.8 ± 11.7</td>
</tr>
</tbody>
</table>

Values are means ± SE. Straight-line distance from the hand to the targets (Pos dist) was obtained using the Euclidean norm in 3-dimensional space. Orientation distance (Or dist) was obtained from the discrepancy between the hand and the object’s principal orientation axis as described in Ref. 25. Target locations and orientations were similar across experiments.

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were performed at a normal, comfortable pace. As in the speed
condition, we used 6 targets, 6 (different) subjects, and 6 repetitions
for a total of 72 paths/target. For consistency, the initial posture
was enforced at the beginning of each trial in two ways: 1) arm posture
was reconstructed from the sensor data and represented with MAT-
LAB three-dimensional graphics we developed and 2) physical markers
in the setup were used to assist the subjects each trial. This
was particularly useful in the abducted posture.

**Target orientation.** In a separate experimental section, we
instructed the subjects to match the orientation of a target cylinder in
two different ways coming from the same position. These motions
were carried out at a comfortable pace. For those targets whose
principal orientation axis was closer to the horizontal, we instructed
the subjects to match the principal orientation axis either as if they
were facing it from above with the palm facing away from the
subject (Fig. 2E) or from below with the palm facing toward the
subject (Fig. 2D). For those targets whose principal orientation axis
was closer to vertical, we instructed the subjects to match it either with
the palm facing left and the thumb pointing up (Fig. 2C) or with the
palm facing right and the thumb pointing down (Fig. 2F). We obtained
the same number of paths per target as in the previous condition.

Proper written consent from each subject was obtained for these
experiments, which was approved by the University Human Subjects
Committee. Twelve right-handed subjects (5 men and 7 women)
participated in the recording sessions (6 in the speed experiment
and 6 in the other 2 experiments). They were not aware of the purposes
of the experiments. None of them had any motor or visual impairment.

**Data processing.** To extract the motion from the sensors output, we
defined the beginning and end of the movement as 5% maximum
velocity along a speed profile. For each trajectory, we determined the points
where the velocity drops to 5% of the maximum and eliminated the
data beyond those points.

Overall, movement speed ranged from 30 (minimum) to 240 cm/s
(maximum) across subjects. Movement velocity was normalized for time
and distance as in Ref. 3. We use their time and distance scaling factors:

\[ c = \frac{V_{\text{ref}}}{V_{\text{max}}} \]

and

\[ a = \frac{d_{\text{ref}}}{d_{\text{max}}} \]

to compute the normalized velocity

\[ V_{\text{Norm}}(t) = c \cdot V_{\text{Data}}(t) \]

from the hand sensor data velocity \( V_{\text{Data}} \), where

\( V_{\text{max}} \)

is the maximum speed, \( d \) is the experimental movement distance,
\( t \) is time, and \( V_{\text{ref}} \) and \( d_{\text{ref}} \) are arbitrary reference velocity and distance
values, respectively, used to scale the data set uniformly. Figure 3A shows
the raw speed profiles for three sample motions to one target and their
respective profiles normalized for time and distance.

For statistical comparison, the sensor position and orientation
outputs were resampled at equal time intervals with a fixed number
of points per path (50 points). Figure 3B shows this for the hand sensor
output of three representative paths, one per speed.

For each experimental condition, we performed standard multivari-
ate analysis of variance on the position, orientation, and postural
paths to test for significant differences as a function of speed, initial
posture, or required target orientation.

We used the Wilks’ test statistic (19) for the individual path points.
This statistic is similar to the univariate F test, which compares the
between sum of squares (expressed in matrix \( H \)) to the within sum of
squares (expressed in matrix \( E \)). However, \( E \) and \( H \) convey multivari-
te information. The ratio \( \Lambda = \text{det}(E)/\text{det}(E+H) \) used by this test
is written in terms of the within sum of squares and products matrix \( E \)
and the total sum of squares and products matrix \( E+H \). The ratio uses the
determinants of \( E \) and \( H \) to examine the separation of mean vectors. This reduces their multivari-
te information to a single scalar.

We have evidence to reject the null hypothesis when \( \Lambda = \text{det}(E)/\text{det}(E+H) \), where \( \alpha = 0.05 \) is the level of confidence, \( p \) is the number
of variables or dimensions (e.g., \( p = 3 \) for paths in 3 space or
\( p = 7 \) for paths in 7 space), and \( vH = k-1 \) and \( vE = n-k-1 \) are the DOF
for hypothesis and error, respectively. The corresponding critical
values for \( \Lambda_{\alpha,p,vH,vE} \) can be found in Table A. 9 in Ref. 19.

**RESULTS**

**Changes in speed.** In this section, we quantify the speed
independence of orientation-matching paths for human arm
motion. Several aspects of the kinematics of movement are
known to be invariant to changes in speed for pointing move-
ments to targets constrained to the sagittal plane (3) and to
targets distributed across the three-dimensional space (18)
where the wrist was constrained. It is unknown how these
results extend to more complex orientation-matching motions
toward targets positioned and oriented differently across the
workspace, where the arm is unconstrained. It is also unknown
how the postural paths behave under these conditions. Other
than the end-point position and orientation paths, we analyzed
the motion of seven joint angles of the arm. Two questions
of interest are whether, in orientation matching, the kinematic
aspects of movement still remain independent from changes
in speed and whether there is coarticulation between changes
in position and orientation of the hand. In addition, we
investigated whether coarticulation is robust to the speed manipulations.

Under three different speed conditions, we found similarities in the position-orientation hand paths and on the postural excursions of the arm (Fig. 4). Of particular interest in this study is the postural behavior, because it has not been previously analyzed in the context of a model that generates paths in posture space. If, as we conjecture, the system computes these paths geometrically, they should be independent of the speed of the motion, so our model can be

Table 4. Effect of instructed target orientation on the arm configuration

<table>
<thead>
<tr>
<th>2 Target Orient</th>
<th>Target 1</th>
<th>Target 2</th>
<th>Target 3</th>
<th>Target 4</th>
<th>Target 5</th>
<th>Target 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm plane ($)</td>
<td>12.07 (1.2\times 10^{-4})</td>
<td>7.04 (0.0015)</td>
<td>14.09 (1.3\times 10^{-4})</td>
<td>7.09 (0.03)</td>
<td>14.61 (2.9\times 10^{-4})</td>
<td>9.17 (0.001)</td>
</tr>
<tr>
<td>Final arm plane</td>
<td>10.38 (2.8\times 10^{-4})</td>
<td>10.5 (5.3\times 10^{-4})</td>
<td>8.11 (0.005)</td>
<td>11.1 (2.3\times 10^{-4})</td>
<td>5.47 (0.04)</td>
<td>8.24 (2.1\times 10^{-4})</td>
</tr>
<tr>
<td>Posture (7 DOF)</td>
<td>0.098±0.0011</td>
<td>0.0306±0.0016</td>
<td>0.016±0.02</td>
<td>0.049±0.015</td>
<td>0.0139±0.012</td>
<td>0.0049±0.004</td>
</tr>
<tr>
<td>Final posture (7 DOF)</td>
<td>0.027</td>
<td>0.097</td>
<td>0.0516</td>
<td>0.019</td>
<td>0.031</td>
<td>0.096</td>
</tr>
</tbody>
</table>

Data are as in Table 3.

Fig. 2. Experimental conditions. A: normal (comfortable) posture corresponding to the initial hand position. B: abducted posture corresponding to the same initial hand position. C–F: instructed hand orientations used to match the given targets for both near-to-horizontal and near-to-vertical tilts. C: match the given target orientation as if coming to it from above. D: match the given target orientation as if coming to it from below. A near-to-vertical target can be matched with the palm of the right hand facing left (E) or with the palm of the hand facing right (F).
used to generate such paths, as shown in the examples used by Torres and Zipser (25).

To address the question of homogeneity of the mean paths for each one of the three speed conditions, we used a ratio from standard multivariate analysis of variance, the Wilk’s $\lambda$ test. The $\lambda$ values obtained were well above the critical value: $\Lambda_{0.05,3,2,105} = 0.885$ for the three $x$, $y$, $z$ parameters in the positional paths; $\Lambda_{0.05,4,2,105}$ for the four quaternion-component parameters in the orientation paths. In addition, the analysis corresponding to the seven joint angles yielded similarity of the three group means, $\Lambda_{0.05,7,2,105} = 0.79$, where $vH = k - 1 = 2$ and $vE = k(n - 1) = 105$ are the DOF for hypothesis and error, respectively, for $k = 3$, the number of speed conditions, and $n = 36$ for six subjects and six repetitions. Table 2 summarizes these statistics. The speed profiles of these motions were unimodal across speeds and similar according to the criterion used by Atkeson and Hollerbach (3). In all the analyses we performed, we failed to reject the null hypothesis concerning similarity of the means.

We also found that coarticulation of the hand changes in position and orientation across the path for all speed conditions (Fig. 5A). Together with the path similarities, this result accounts for a single geometric strategy robust to changes in the temporal dynamics of the motion.

**Manipulation of the initial posture.** The arm paths generated by the modified gradient method resemble behavioral paths in response to orientation-matching motions, and, as such, several of its features compare to those known from actual arm movements (25). For example, simulated motions of this kind reflect the dependence of final posture from the starting posture observed in pointing (21) and reach-to-grasp movements (8). Here, in an orientation-matching task, we used two different initial postures (normal and abducted) to address two questions: 1) whether, besides the known effect on the final posture, the initial posture has a significant effect on the whole postural and hand paths; and 2) whether coarticulation is robust to this manipulation.

The use of an abducted initial posture requires more effort to solve the movement. Because of redundant DOF, there are several possible strategies for coping with this difficulty. For instance, subjects could first reset the posture to a normal starting configuration and then move to the target. This first part of the movement would require traversing a path in posture space that does not result in motion of the hand. The experimental data, however, show a strategy that is consistent with the model’s output: subjects’ movement from the given starting configuration in posture space results in hand motion that continuously decreases the remaining distance to the target (Fig. 5B).

The statistical analysis of the kinematics data due to the two different starting postures shows a significant effect on the resulting hand positional and orientation paths (Table 2), as well as on the postural paths and on the plane of the arm (as defined in Ref. 18) (Table 3). In contrast, consistently for each
subject, the coarticulation of hand changes in position and orientation holds across the movement paths to all targets independent of changes in the initial posture. Figure 5B shows this result for one subject’s motions to one target. A similar result was obtained across all subjects. This suggests a unique cognitive strategy based on extrinsic goals, such as those related to distance.

Change in target orientation. Previous data from humans (22) and nonhuman primates (14) have shown that both the orientation and the location of targets in space affect the final posture of the arm. This raises the question of whether these results extend to the entire postural path. According to our model, motions that begin at the same hand configuration but require matching different orientations at the same space location should change the postural and hand paths but not the coarticulation of the changes in hand position and orientation along the path.

Statistical analysis on the subject’s endpoint paths (all λ well below critical value at the 0.05 α level; see Table 2) and postural paths, as well as the plane of the arm (see Table 4), reveal differences as a function of required target orientation.
In addition, coarticulation generalized across target locations and orientations (Fig. 5C), even for those motions requiring target orientations that resulted in an uncomfortable final posture.

DISCUSSION

We have previously proposed a novel approach to movement control whereby a geometric stage mediates the transformation from sensory input to motor execution. The motivation stems from two empirical sources: 1) neurophysiological data from posterior parietal cortex (PPC), which suggests a dynamics-free representation of movement (16) along with evidence for multisensory integration and correlates of coordinate transformations (1); and 2) experiments involving humans as evidence for speed-independent paths during pointing in two (3) and three (18) dimensions.
Our solution is based on a differential approach, so at each time step, it requires input regarding present target information combined with present posture to compute the hand-target discrepancy. This input can but does not need to be continuously monitored. Offline integration of the gradient vector for \( n \) steps is also possible to compute the full or partial path to the target for action. In addition, estimation of target information is feasible without actual access to it. There is evidence that in PPC neurons can be activated by the plan to use a specific effector without spatial information (6).

The hand-target discrepancy vector, for which the motor system needs to code, must arise from the mixture of very different representations, both extrinsic and intrinsic in nature. The consideration of arbitrary coordinate systems to represent movement goals and parameters, along with the invariance of the brain solution to arbitrary coordinate transformations, intimately links this problem to the concepts and methods of Riemannian geometry. It is in this sense that the approach we propose addresses all of these issues and gives a general equation

\[
dq^\text{task} = (G_{q}^{\text{task}})^{-1} (\mu^\text{task} \circ f) \Delta t
\]

which provides a principled way to compute the autonomous flow of geometric motion as a function of the task in both the task and the posture space. This principle is the same regardless of the coordinate representations of choice.

Initially, the job of the geometric stage would be to find optimal strategies to solve the task geographically (as when an athlete imagines a motion without performing it), but later, as the movement becomes more automatic through practice and repetition, the role of the geometric stage would switch to that of a “supervisor,” who is able to correct for errors or perturbations online. In this way, the execution system would not be tied up with the problems of learning a new task, adapting to sudden changes in the goals of a task, or responding to changes in the task’s context.

This framework not only endows the motor system with the ability to simulate motion but also makes possible the exchange of information between the subsystem linked to the geometric stage and that concerned with the execution of these geometric strategies. This is because the output signal of the geometric stage is expressed in parameters of the same kind as those needed by the execution system to compute the dynamics of motion, and yet it carries task-dependent cognitive information.

The separation that we propose between learning (geometric strategy formation) and automaticity (temporal-dynamics optimization) cannot be captured in the present neurophysiological data. These data come from overlearned and too simplistic reaching movements that have already become automatic (ballistic), as shown in their bell-shaped speed profiles. A fair test to this theory will come from new experiments simultaneously recording activity from PPC and M1 either as the animal learns a new task or in the presence of a sudden perturbation that calls for new strategies. In these cases, the prediction of this theory is that the PPC signal will temporally advance that of M1, canceling or reversing this effect as time progresses and the motion becomes automatic. We know from recent transcranial magnetic stimulation experiments that PPC but not M1 is critical to adjust to sudden target displacements during reaching movements (7).

In the context of arm movement, which is modeled by using joint angles to represent postures, the output signal of the geometric stage is a directional unitary vector that indicates how much each joint angle in the arm should change to incrementally bring the hand closer to the target. This joint-angle velocity vector is required in the computation of kinetic and potential energy (5) necessary to take into consideration gravity, inertia, changes of mass, etc. In particular, the kinetic energy, \( T = \frac{1}{2} m v^2 = \frac{1}{2} m (ds/dt)^2 \) involves explicitly the line element \( ds \), hence it depends on the geometry of space, which in the general case that interests us may be non-Euclidean: \( ds^2 = \sum_{ij} g_{ij} dq_i dq_j \). The quantity \( ds^2 \) is important in our distance-based formulation because it does not change regardless of the coordinates employed (12). It is invariant to any particular reference system. The quantities of \( g_{ij} \) on the other hand are covariant; they change as a function of the coordinate representation chosen to better capture the task at hand, which in turn changes as a function of the posture \( q \). The special metric tensor \( G \) plays a fundamental role in our formulation. It allows the development of a complete geometric analysis, not only of the three-dimensional space, but also of the space of \( n \) dimensions. This is significant because, as we have emphasized, a given task may span many dimensions, which in turn have to be translated into those of the higher-dimensional posture space.

Parameters of both disparate worlds are intimately related and seem to be mutually optimized (10). In addition, a recent prismatic-adaptation study suggests that “what is learned is not simply a new endpoint trajectory but pertains to the movement of the whole arm” (4). Such relationships are captured in our formulation in three ways: 1) in the form of a pull-back action, a geometric operation \( (r \circ f) \) that expresses parameters of one space as functions of parameters in another space; 2) in the optimization of this pullback, which produces a solution in both spaces; and 3) in the action to preserve in \( Q \) the notion of distance in \( X \) given by \( G_{\nu v} = J^\gamma G_{\gamma \gamma} J \) to build a local isometric embedding of \( X \) into \( Q \) and give a one-to-one correspondence between the tangent space to \( X \) and that tangent to the subspace of \( Q \) which the embedding defines.

This general definition enables in-depth study of the geometry of various realistic goal-oriented behaviors in systems with redundant DOF. The specific example presented in this paper tests predictions concerning reach-to-grasp with orientation-matching motions. One of the predictions concerns the parallel control of the hand transport and orientation phases along the movement. Such coarticulation naturally emerges from the form of the proposed objective function, where two terms account for the position and orientation differences from the hand to the target. This scalar function amounts to the measure of distance in a four-dimensional space spanned by the three components of the positional vector and the orientation discrepancy parameter. Because the geometry of task space is preserved, these four dimensions are transferred to the space of the arm, where seven DOF have to be controlled. Out of these seven DOF, only those corresponding to a four-dimensional
subspace are recruited, leaving the other dimensions redundant for this task. Figure 5D illustrates this for one target. The position and orientation differences depend on all of the arm joints in a redundant way. Thus changes in any of the individual joint angles could potentially decouple the control of the hand changes in position from its changes in orientation along the path. The data, however, agree with the model’s predictions of coarticulation and show that this general outcome is robust to dynamics-related manipulations. This is consistent with the proposed idea that the transformation from intrinsic goals to motor commands may be governed by geometric principles.

Across all three experimental conditions we tried, the position and orientation discrepancies decreased at the same rate. This contradicts the intuitive belief that, in reach-to-grasp movements, distal DOF spanned by the wrist and proximal DOF related to the shoulder act in a decoupled way. A simplifying strategy of this kind, whereby DOF at the wrist would be primarily concerned with the rotation of the hand, whereas those at the shoulder would mainly control the transporting of the hand to the target location (2, 15), is not consistent with the subjects’ performance in response to this task.

The “division-of-labor” strategy can be achieved under cognitive control when the task is different. In fact, we have observed two instances in which subject’s motions show an interesting outcome. Under specific instructions, they are able to break down the movement toward a target into discrete segments where the rate of change of transport and orientation differs. Subjects can also alter coarticulation when obstacles are positioned on the way to other targets (Torres EB, unpublished observations). In both instances, the speed profiles are not unimodal and the coarticulation parameter $\alpha$ is no longer constant along the entire movement path. In the model, it is also possible to manipulate the $\alpha$ ratio by changing the weight placed on either phase of the motion. This feature permits the simulation and empirical assessment of more interesting tasks. However, human subjects show simultaneous rather than serial coordinated control of hand position and orientation across all three experimental conditions.

Present models cannot simulate realistic paths with redundant DOF in the arm. Up to this point, in complex motions of this kind, it has been very difficult (if not impossible) to engineer the coarticulation result we report here. Likewise, it has been challenging to computationally reproduce experimental pointing motions where the initial posture of the arm affects the final posture (21) or where changing the required target position and orientation affects the arm posture as a whole (22).

Our treatment of geometry independent of temporal dynamics makes it possible to account for all of these behaviors with a computational model. The observed similarity of postural and endpoint paths under three different speeds is consistent with the idea of our proposed intermediate geometric stage. It extends former results from constrained pointing motions (3, 18) to more complex orientation-matching movements. Furthermore, we provided postural data in agreement with the model simulations to account for the effect of changes in initial posture and required target orientation. Any model of motor control that resolves the detailed temporal profiles of movement must account for the experimental observations presented here.

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