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Planning Movements in a Simple Redundant Task

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Summary

There are infinitely many different combinations of arm postures which will place the hand at the same point in space [1]. Given this abundance, how is one configuration chosen over another? Two main hypotheses have been proposed to solve this problem [2]. Postural models suggest that the posture adopted is purely determined by the desired hand position (known as Donders' law) [3, 4]. Transport models suggest that the adopted posture depends on where the hand has moved from. A specific transport model, the minimum work model, has been proposed in which the adopted posture is the one that minimizes the amount of work required to move the hand to the new location [5]. The postural model predicts that the posture will be independent of where the hand has moved from, whereas the transport models predict that the posture will depend on the previous posture. We have devised a simple redundant task—touching a target bar using a hand-held virtual stick—to examine these models. The results show that neither model alone can account for the data. We propose a control planning strategy in which there is a combined cost function that has both a postural term as well as a transport term.

Results and Discussion

To distinguish between transport and postural models, we used a simple redundant task—touching a target bar using a hand-held virtual stick (see Figure 1). This allows two rotational degrees of freedom: the first around the long axes of the upper arm (humeral rotation) and the second around the forearm (pronation/supination, which we term "forearm rotation"). However, the task is specified by only one degree of freedom, and therefore the task could be achieved by humeral or forearm rotation alone or by an infinite number of combinations of the two. The stick task was chosen for two reasons. First, the inertia of forearm rotation is two orders of magnitude smaller than humeral rotation—a ratio preserved by using a mass-less virtual stick. As work is proportional to inertia, this causes the minimum work model (a transport model) to strongly and predictably favor forearm over humeral rotation. Second, humeral and forearm rotation are controlled by separate nonoverlapping groups of muscles, which minimizes biomechanical constraints and thus allows an investigation of neural principles of planning [6].

In the first experiment, subjects used the stick to alternately touch two targets which were at the same height and either 16 cm apart (insert in Figure 2, left) or 24 cm apart (insert in Figure 2, right). On each trial, the targets were displayed at one of five heights. The final arm postures, that is humeral and forearm rotation, for each of the targets are shown in Figure 2, where color denotes the height of the target.

Subjects assumed distinct postures depending on target height and width. Subjects produced more humeral than forearm rotation, and their movement paths in joint angle space were approximately straight (data not shown). With increasing target height there was less humeral rotation and concomitantly more forearm rotation. This pattern was observed in all seven subjects.

We compared these postures with predictions based on the minimum work model [5], which suggests that the peak kinetic energy, which scales with inertia, is minimized during a movement. For quantitative predictions, the lower arm was approximated as a cylinder of radius $r = 4$ cm and length $l = 40$ cm, with uniform density and mass M, yielding a humeral:forearm rotation inertia ratio of 67:1 ($Ml^2/3$:$Mr^2/2$). The upper arm was not modeled, as it does not contribute significantly to the task. As work is proportional to inertia, this principle predicts that forearm rotations will be very heavily favored over humeral rotations—which conflicts with our data. We generated minimum work predictions for the two final postures in each trial by predicting them based on the starting posture. This root-mean-squared prediction error for humeral and forearm rotations was 18.7° and 38.9°, respectively. Predictions remained poor when, instead of calculating the ratio of inertias, we fit it to the data (optimal ratio 1.39:1 instead of 67:1; errors of 3.9° and 11.2°, respectively).

As an alternative, we modeled the posture data with a quadratic regression model, an implementation of Donders' law and thus a postural model. Here, both the forearm and upper arm angles were fit as $\alpha_1 + \alpha_2 h + \alpha_3 w + \alpha_4 h^2 + \alpha_5 w^2 + \alpha_6 hw$, where h and w are the target height and width respectively (gray lines in Figure 2). Stepwise regression revealed that only $\alpha_{1\text{–}3,5\text{–}6}$ and $\alpha_{1,4,6}$ were significant at the $p < 0.05$ level (only these were used in the model) for the upper arm and forearm posture, respectively. The correlation coefficients (r^2) for the humeral and forearm rotations were 0.997 and 0.950, respectively ($p < 0.001$ for both cases). The root-mean-squared prediction errors for the humeral and forearm rotations were 0.6° and 1.4°, respectively.

The first experiment was well fit by a postural model but not by a transport model, suggesting that target posture is not affected by the start posture. This predic-

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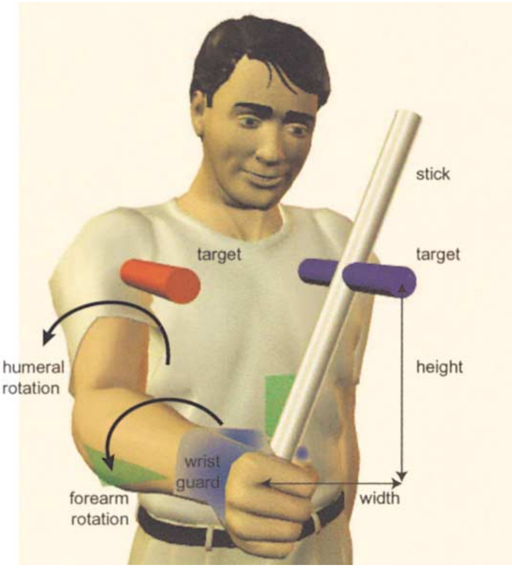

Figure 1. Schematic of Experimental Paradigm

Subjects held a virtual stick with which they were required to touch a cylindrical target, rotating around the long axis of the upper arm (humeral rotation) and around the long axis of the forearm (forearm rotation).

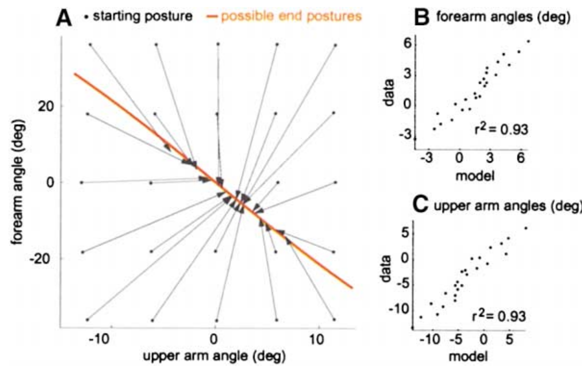

Figure 3. Results of Moving the Stick from Different Starting Postures to a Single Target

Panel (A) shows the start postures (black dots) and corresponding target postures (arrow tips). Postures are averaged over subjects and repetitions. Panels (B) and (C) show plots of the 24 regressed versus measured forearm and upper arm angles, respectively.

tion was tested explicitly by having subjects touch a single target from a range of different start postures in the second experiment (see Experimental Procedures for details). Figure 3 shows, however, that there is a systematic effect of start posture on end posture. This effect is accurately modeled by a linear regression, in which $u_e = \alpha_1 + \alpha_2(u_s - \bar{u}) + \alpha_3(f_s - \bar{f}) + \bar{u}$ and $f_e = \alpha_4 + \alpha_5(u_s - \bar{u}) + \alpha_6(f_s - \bar{f}) + \bar{f}$, where u is the upper arm angle, f is the forearm angle, the bar denotes the mean end angle over all movements, s denotes the start angle, and e denotes the end angle. In other words, the end posture is linearly related to the difference between the start posture and the mean final posture. The correlations (r^2) are high, both for upper arm and forearm, at 0.94 (0.78–0.94 for individual subjects) and 0.94 (0.77–0.94 for individual subjects), respectively ($p < 0.001$ for all regressions).

The regression values did not change when, instead of using the mean posture as the reference posture, we optimized the reference posture with respect to the regression. The group mean upper arm and forearm angles were 1.59° and −3.76°, compared to the optimized reference upper arm and forearm angles 1.59° and −3.6°. We found the influence of start posture to be linearly related to its distance in joint space from a reference target posture.

A pure postural strategy fits the first experiment well, but it cannot explain the systematic effect of start on end postures in the second experiment. This concurs with reports from several laboratories that have found deviations from postural laws for arm movements in man [5, 7] and in monkey [8].

In transport models, the path taken is critical, and these models will predict different target postures depending on the start posture. For instance, the minimum work model states that the peak work required to execute an arm movement should be minimized, which would determine the end posture [5]. In our task, the inertia (which is proportional to peak work) for rotating around the upper arm is far greater than rotating around the forearm, leading the model to erroneously predict that movements should be executed almost solely through forearm pronation/supination. The problem for models relying purely on the path taken is that they tend to overestimate the effect of start posture, which, although systematic, was relatively weak in our experiments.

Medendorp et al. (2000) [9] recently showed evidence that end posture is influenced by start posture but that

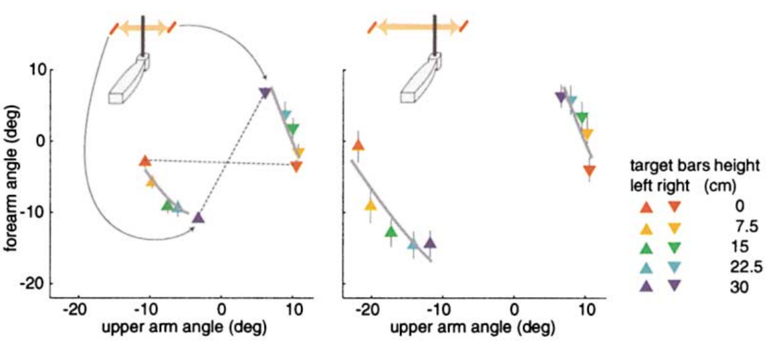

Figure 2. End Postures Assumed when Moving the Stick Repeatedly between Two Targets of Equal Height

The upward triangles are for the left target, and the downward triangles are for the right target, with color indicating different target heights. The left panel shows the results for targets 16 cm apart, the right panel for targets 24 cm apart. Postures are averaged over subjects and repetitions and shown with 95% confidence limits. The gray lines are fits of the quadratic regression model.

for each individual start posture Donders' law is obeyed. However, they make no quantitative statement about the modulation. Somewhat similarly, Rosenbaum suggested another model, in which the end target posture is the average of stored postures weighted according to the energetic cost required to reach them and also their closeness in accomplishing the task [10]. Since its current formulation is not falsifiable (the amount and nature of stored postures is not prespecified and can also be learned), the only qualitative statement one can make is that it would require a large number of stored postures to be able to capture our data. However, Rosenbaum's idea of using a cost function that has both a postural as well as a path component makes good qualitative sense. We propose a cost function that minimizes both some aspect of posture, as well as minimizing the path taken from the start posture.

Specifically, for the first component of the cost we use Baud-Bovy's idea of a reference posture [11]. Postures tend to be as close to this reference posture as possible, given the task constraint. The second component of our cost function then adds a dependency of the start posture, in which the distance travelled is assumed to be minimized. In our experiment, we find that the deviation from the reference posture is linearly related to the distance of the start posture to the reference posture in joint coordinates.

Two open questions remain. First, at present there is no a priori way of determining the reference posture, since all movements start from somewhere [11]. One empirical approach is to define the mean of all postures as the reference posture [11] or to optimize the reference posture given the experimental data. Interestingly, both approaches lead to highly similar reference postures in our data, which lends validity to our proposition. Second, why there should be a trade-off between distance travelled and nearness to a reference posture remains unknown.

Experimental Procedures

Right-handed subjects (seven) who were naive to the purpose of the experiment gave their informed consent and participated in experiment 1; eight different right-handed subjects participated in experiment 2. Subjects grasped a lightweight manipulandum while resting their elbow on a pad. Movements were limited to forearm pronation/supination and humeral rotation which keep the forearm in the horizontal plane (Figure 1). To prevent any wrist flexion/extension, subjects wore a wrist guard (maximum movement, 0.5 cm). The manipulandum position and orientation was sampled with an Optotrak 3020 at 100 Hz. Instead of a manipulandum, subjects perceived themselves as grasping the bottom end of a 40 cm long virtual stick with a diameter of 0.8 cm. The virtual stick (but not the arm) was displayed using a stereoscopic visual feedback system with a refresh rate of 60 Hz (for full details of the system, see [12]).

The humeral rotation was taken as the angular deviation in the horizontal plane of the forearm (elbow to manipulandum grip) relative to the forearm at rest (clockwise rotations are positive). The position of the manipulandum grip was calculated from the Optotrak data [13]. The position of the elbow in the reference frame of the manipulandum was calculated by determining which point in Cartesian space and manipulandum space remains fixed throughout the experiment. The only point for which this is true is the elbow. Forearm rotation was taken as the manipulandum's angular deviation from the upright position in the plane perpendicular to the direction of the forearm. The angle resolution was better than 0.05°.

In all experiments, subjects initiated trials by moving the base of the stick to within 0.2 cm of the rest position, displayed as a red line. In this rest position, determined at the beginning of the experiment, the subject's arm was relaxed, with the forearm pointing straight ahead.

The first experiment explored how subjects used their two degrees of freedom when moving a stick repeatedly between two targets bars of equal height in an otherwise unconstrained fashion. The repetitions were used to see what postural pattern subjects would fall into. Two 16 cm deep target bars of 1 cm diameter were displayed 0, 7.5, 15, 22.5, or 30 cm above the rest position: one 8 cm to the right in blue, and the other either 8 cm or 16 cm to the left in red. Subjects were instructed to "touch the red bar anywhere with the stick." Movements ended when the stick came within 0.4 cm of the target bar, signaled by a tone and target colors switching. Each trial consisted of 11 consecutive bar touches. Subjects were familiarized with the setup with four trials at 30 cm height and 8 cm width and four trials at 0 cm height and 8 cm width. Subjects then had two trials at each height and target width presented in a pseudorandom order. Rest periods were interspersed every eight trials.

In the second experiment, we examined parametrically the relationship between start and end posture for a single target. This was achieved by replacing the right target bar in experiment 1 with a target plane. Subjects were instructed to "lie the stick in the plane." Note that in contrast to a target bar, there is only a single (specified) arm posture in which the stick can be laid in the plane. The plane was 16 cm deep and 40 cm high, placed −10, −5, 0, 5, or 10 cm to the left of the rest position, and tilted −36°, −18°, 0°, 18°, or 36° clockwise (with zero being vertical). Subjects were alternately presented with a target plane and then a target bar 22.5 cm above the rest position. The target plane for each of the 24 conditions was presented in a pseudorandom order 11 times. The 0 cm/0° condition was omitted because the stick would have been touching the target bar.

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