can also be used for simulations of movements that are more complex than reaching. For example, in the study of movements involving moving targets.

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Shifting frames of reference but the same old point of view

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Abstract: Models of central control variables (CVs) that are expressed in positional reference frames and rely on proprioception as the dominant specifier of muscle activation patterns have not yet been shown to be adequate for the description of fast, voluntary movement, even of single joints. An alternative model with illustrative data is proposed.

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Twisted pairs: Does the motor system really care about joint configurations?

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Abstract: Extrapersonal frames of reference for aimed movements are representationally convenient. They may, however, carry associated costs

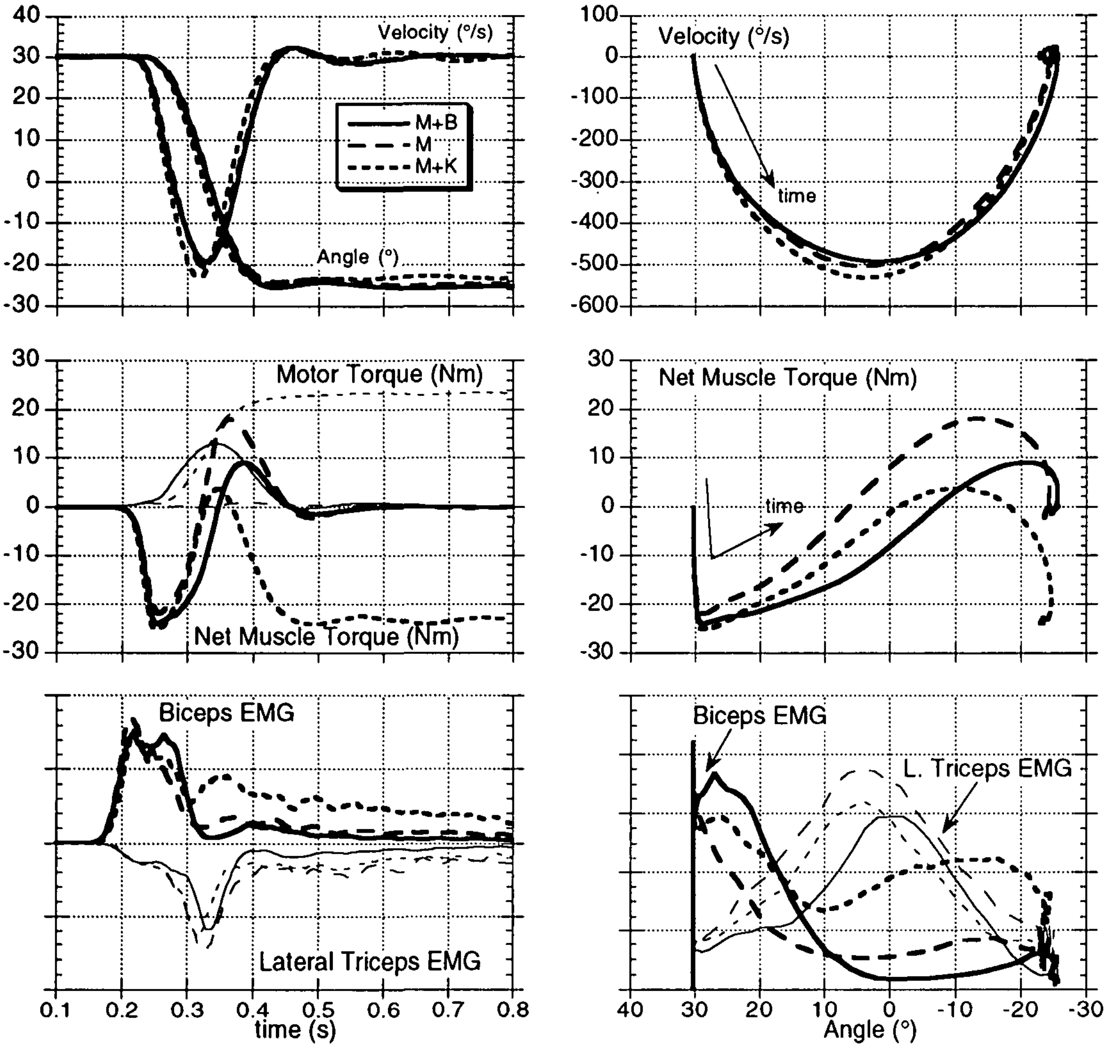

Figure 1 (Gottlieb). Movements of three dynamically different loads. Average of 10 movements over 54° with known inertial, viscous, and elastic loads. Similar kinematic traces on the left are produced by very different muscle forces that emerge from different muscle activation patterns as revealed by the EMGs. Net muscle torque is equal and opposite to the sum of the motor and inertial (limb plus manipulandum) torque components. It is well correlated with the EMG patterns. Neither muscle torque nor EMG patterns can be determined from the kinematics alone without reference to the dynamics of the land moved by the limb.

Kinematic, force, and EMG variables are illustrated as functions of time on the left and as functions of joint angle on the right. The instructions to the subject were only to be "fast and accurate" and it was in retrospect that the similarity of the movement trajectories (particularly with B & K loads) was noticed. In general, changes in load alter the trajectory, but the degree to which they do so is strongly dependent on the type of load, its magnitude, and the strength of the subject. This figure may be considered from two points of view. One is that EMG patterns are mostly proprioceptively driven consequences of kinematics. The other is that EMG patterns are mostly consequences of centrally specified patterns (CVs). The choice is left as an exercise for the reader.

when the movement is executed in terms of the complex coordination of multiple joints they require. Studies that have measured both fingertip and joint paths suggest the motor systems may seek a compromise between simplicity of extrapersonal spatial representation and computational simplicity of multi-joint execution.

This commentary focuses on the application of Feldman and Levin's (F&L's) EP model to multi-joint reaching movements. F&L suggest that multi-joint movements are represented as shifts of a reference frame for the limb endpoint in extrapersonal space (sects. 9 and 11.2). External space provides a representationally intuitive framework for the CNS to code target locations for movements. However, it does not guarantee a simple or intuitive system for controlling joints and muscles, because the varying kinematics and dynamics of the arm make the transformation from a set of muscle commands to locations in external space very complex. Because the human arm is redundant, representing movements in terms of locations in external space also leaves the motor system with the ill-posed problem of selecting just one of the many possible ways that the joints can move the endpoint through external space. The selection problem is often associated with prior trajectory planning, especially in robotics, the control problem arises during movement execution. F&L's EP model does not address either problem adequately.

Models based on extrapersonal representation of movement often ignore the control difficulties in generating the commands that produce such regular features (e.g., Hogan 1984). The geometrical decomposition approach of sections 11.2 and 11.3 does not truly solve the selection problem, because the set of joint-pair weightings is just as underdetermined as the joint angles; nor do they guarantee solutions to the control problem that are easy to implement. We suggest that the motor system may try to simplify the control functions required to execute multi-joint movements.

Preferring multi-joint patterns that are simple to execute would also help answer the selection problem.

We have recently measured the spatial path of the fingertip, and the shoulder, elbow, and wrist joints during anterior posterior, lateral, and diagonal horizontal right-handed planar pointing movements (Haggard et al. submitted). We present three results that suggest the motor system represents and selects some joint paths that simplify the control of multi-joint movement. First, we noticed a tendency for one joint to rotate much more than the others. Lateral movements were performed largely by shoulder

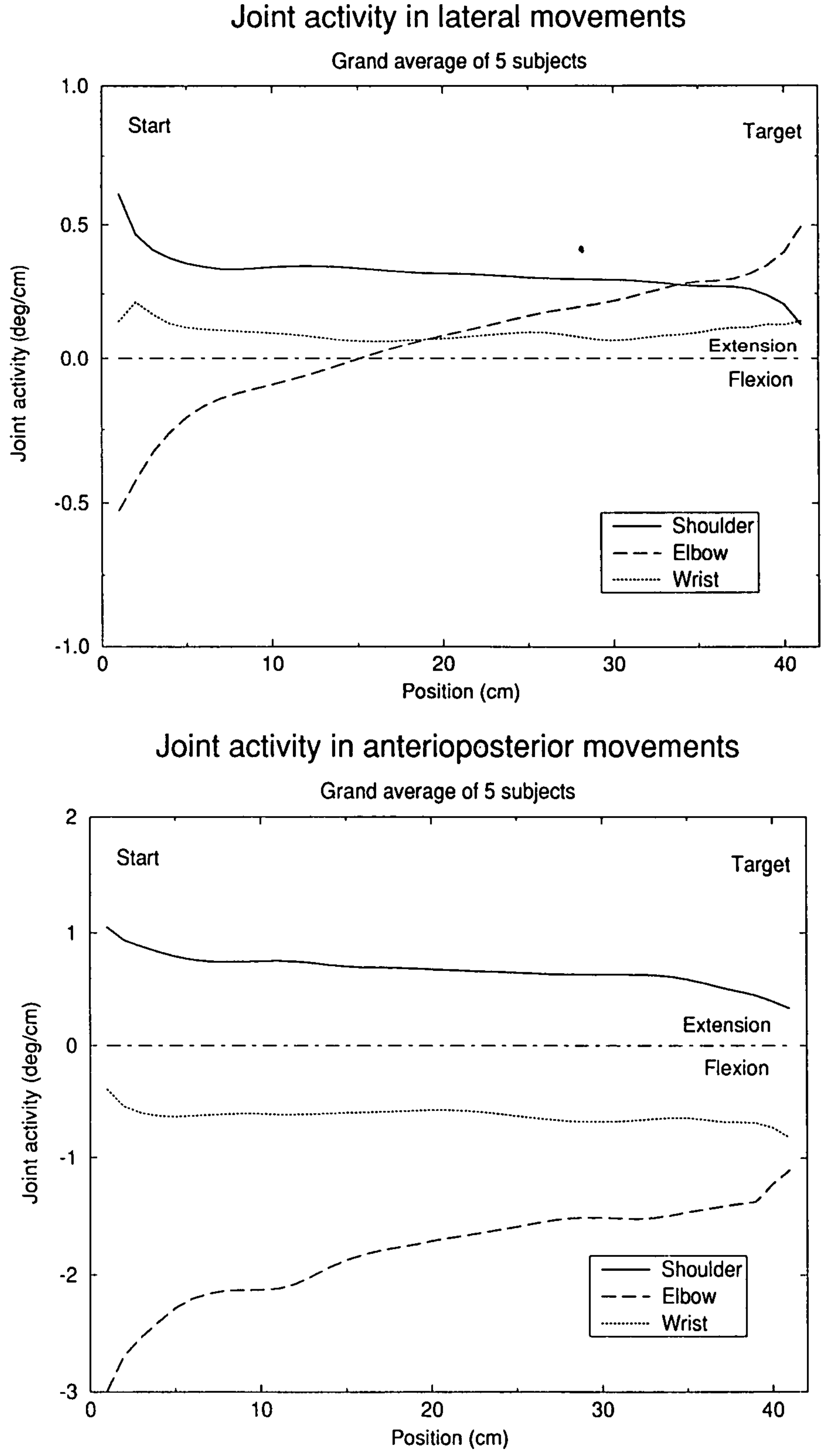

Figure 1 (Haggard et al.). Rotation of shoulder, elbow, and wrist joints during each cm of the hand's progress along a start-target axis in lateral movements from left to right (top), and in anterioposterior movements from distal to proximal (bottom). Traces show a grand average of 12 movements from each of 5 subjects. The cumulative integral of each trace gives that joint's spatial path.

rotation, and movements from proximal left to distal right were performed largely by elbow rotation. More important, the primary joint in each case moved essentially without reversals; the non-primary joints often involved considerable reversals. This result implies a simple, invariant control strategy for the primary joint in each case, with the remaining joints accommodating the primary joint. Decomposition of an extrapersonal space representation using weighted joint pairs cannot explain this result. We suggest that the motor system may simplify reaching movements by selecting a single joint to produce the bulk of the movement. The primary joint may use simple (interpolative?) control, whereas the paths of the other joints may be coordinated so as to prevent excessively curved paths in extrapersonal space. That is, the motor system may prefer to sacrifice the representational convenience of an extrapersonal frame of reference for computationally simple pseudo single-joint movements.

Second, we found that movements from distal left to proximal right, and to a lesser extent anterioposterior movements, involved more equal amounts of shoulder and elbow rotation. These movements cannot be reduced to pseudo single-joint movements, and the motor system must confront the arm's redundancy head-on. Indeed, the hand's spatial paths in these movements showed greater variability than those of movements with a clear primary joint. Analogous results were seen by Atkeson and Hollerbach (1985), but did not attract comment. This increase in variability suggests that executing coordinated multi-joint movements presents a sufficient computational problem to warrant trick solutions where possible, such as using primary joints, which simplify coordination. Extending EP hypotheses to multi-joint movements assumes that multi-joint coordination follows straightforwardly from control variables in extrapersonal space, but our variability data suggest that this transformation has a clear computational cost.

Third, we averaged the amount of rotation at each joint over each cm of the hand's spatial path between start and target. In a sense, this representation corresponds to the way the motor system inverts the Jacobian matrix of the arm. It is not surprising that the resulting joint rotation patterns (Fig. 1) differ markedly between anterior posterior and lateral movements. For example, the elbow reverses in lateral but not in anterioposterior movements. Further, the contribution of shoulder and elbow rotation to the instantaneous hand displacement varies during the course of the movement. The converging shoulder and elbow traces suggest different patterns of inter-joint coordination are used to produce hand translation at different stages. F&L's treatment of the joint pairing (W_{ij} in sect. 11) suggests the pairings are control variables that are normally calculated and fixed in advance for a given motor task. Our evidence suggests that the pairings are not held constant throughout the movement. The clear tails on the joint rotation profiles near the start and target suggest that the inter-joint coordination is actively modulated, perhaps to produce a desired hand path in extrapersonal space.

In conclusion, our evidence suggests that the selection of joint activity and of inter-joint coordination patterns is not independent of the endpoint trajectory as the Feldman and Levin model proposes. Further, the motor system seems to select both joint and endpoint parameters in a way that simplifies the computations required for coordinated movement execution. An extrapersonal frame of reference is a convenient representation, but it may not be appropriate for the problems the motor system faces in controlling multi-joint movement.

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Is λ an appropriate control variable for locomotion?

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Abstract: The lambda model predicts that the command received by each motor nucleus during locomotion is specific for the joint at which its muscle acts and is independent of external conditions. However, investigation of the commands received by motor nuclei during fictive locomotion and of the sensitivity of these commands to feedback from the limb during locomotion indicates that neither condition is satisfied.

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