TOWARDS THE PREDICTION OF THREE-DIMENSIONAL DYNAMIC POSTURES: AN EXPERIMENTAL SCHEME TO IDENTIFY AND QUANTIFY TASK EFFECTS FOR DISCRETE SEATED REACHING MOVEMENTS

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TECHNICAL REPORT

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ABSTRACT

This paper describes a novel scheme to empirically study three-dimensional dynamic postures. The scheme is driven by a statistical model which combines two sub-models: one with three coordinates of the hand as independent variables, and the other with various hypothesized factors. Decoupling two components of the model differentiates the effects of end-effector position and those of various task factors on dynamic postures. Postural profiles are assumed to be interpolatable and extrapolatable across a range with invariant movement condition. The use of this experimental scheme was illustrated by testing the effects of 1) hand movement direction and 2) completion time on dynamic postures during seated reaching movement in a pilot experiment. By having a subject perform movements with hand trajectories intersecting each other, a set of instantaneous postures with common hand positions was obtained for statistical analyses. The effects of the two task factors, hand motion direction and movement completion time, on the overall instantaneous postures and individual joint movements have been examined. Initial results suggest the hand motion direction is a significant task factor whereas the movement completion time is not significant. It was also found that the faster completion time in a motivated speed mode used in this study was comparable to the time pre-determined by the MTM system. The understanding of human postural control as well as the implications for developing dynamic posture prediction model gained from the experiment are discussed. Recommendations for future research directions are also presented.
INTRODUCTION

One obstacle to the development of three-dimensional dynamic biomechanical models has been the lack of an experimental paradigm to study normal human postures and movements under various operational settings. The need to model and simulate human physical activities, by describing postures dynamically and three-dimensionally, is receiving increasing attention in the field of ergonomics (Chaffin, 1992; Ayoub 1994). However, it has not been fully recognized that an initial but essential step towards the development of such models is the ability to first devise experiments to capture normal movements in three dimensions, and then to quantify how the dynamic postures can be affected by various task or environmental factors. An experimental paradigm with this ability would facilitate the development of statistical models from the synthesized effects. It would also lead to the establishment of a behavior data-base for the development, and more importantly, the empirical validation of other types of models.

Most of the models that have been developed to drive three-dimensional dynamic simulations of human movement exist in the computer science domain (Calvert et al., 1993; Wilhelms, 1987; Armstrong et al., 1987; Badler et al., 1987; Monheit et al., 1991; Phillips, 1991). None of these models are based on real empirical data, but rather employ heuristic algorithms or rough estimates of human postural kinematics (Jung et al., 1994). Therefore the application of these models in biomechanical or ergonomic analysis remains questionable until certain validation has been done.

There are many difficulties involved in the empirical investigation of dynamic postures. First, the amount of data yielded from multi-segment movements can be overwhelmingly voluminous. For instance, suppose a set of ten joint landmarks on a human body is being measured to describe a posture, with each landmark containing three data points as its three Cartesian coordinates. If a sampling rate of 25 HZ is used to record a movement over 2 seconds, 1500 data points will be generated. Compared to
static analyses, tremendously more effort is required in the data management, pre-
processing, or data-reduction before any statistical testing can be conducted.

Secondly, there is no systematic way to choose the appropriate dependent
variables. A straightforward way is to examine the entire motion profiles to compare
dynamic postures under different prescribed conditions, which is rather tedious and
cumbersome. On the other extreme, assessing the initial or ending postures is convenient
but rarely provides any information about the dynamics. Currently a measure with both a
manageable data scale and dynamic information is not available.

Thirdly, most movements under operational settings are target-directed. They are
dictated but not completely determined by the end-effector (usually the hand) position,
since the human body is kinematically redundant. Therefore, discerning whether the
variations are caused by different end-effector locations or various task factors can be
problematic.

Two task factors inherent to any generic movement are 1) the time to complete a
movement, and 2) the intended direction of an instantaneous posture. Many studies have
addressed the completion time or the movement speed issue, with the focus on the upper
limb (Morasso, 1981; Morasso and Mussa-Ivaldi, 1982; Morasso, 1983; Hogan, 1984;
Flash, 1990). Few studies in the existing literature, however, have investigated how the
completion time would affect motion profiles of a multi-segment movement, in other
words, will the postural behavior for a self-paced, voluntary movement differ from a
movement with a motivated speed? A model with this issue elucidated will have better
integrity and applicability.

With regard to the second factor, several previous investigations have
demonstrated the effects of direction-dependent stiffness (Flash, 1987), limb inertia
(Gordon et al., 1994a, 1994b), and overall control strategy (Karst and Harsan, 1990).
Although these studies have all suggested that spatial direction of movement plays an
important role in arm movement performance, it has not been clarified that whether the
locational effect or the directional effect was the true cause of the variation in performance measures. Furthermore, these studies again have only addressed the arm movements in the horizontal plane. In general, this type of research, performed in the context of motor control and motor performance, is not inclusive nor quantitative enough to be useful in developing three-dimensional dynamic posture models.

The purpose of this study is to establish a scheme to empirically identify factors affecting three-dimensional dynamic postures and elucidate their effects. The scheme is driven by a statistical model which combines two sub-models: one with three coordinates of the hand as independent variables, and the other with various hypothesized factors. Decoupling two components of the model differentiates the effects of end-effector position and those of various task factors on dynamic postures. This study also uses the experimental paradigm to examine whether and how hand movement direction and completion time affect dynamic posture of the torso and the upper extremity during seated reaching motions. The seated reaching movements considered are volitional, non-ballistic, non-cyclic, and right-handed. The left hand and left arm are assumed not to pose any restraint to the reaching motions and are not studied in the current investigation. A pilot study with one subject is reported.
METHODS

Model Description

The configuration of the biomechanical system of concern can be adequately represented by a chain-like linkage system as in Figure 1. This linkage is composed of four links: torso, right clavicle, right arm, and right forearm. Given three-dimensional locations of the right hand with respect to a specified reference frame, the configuration of this linkage system is indeterminate, referred to as the problem of kinematic redundancy. It is usually postulated that the determination of preferred postures is accomplished by an inherent strategy used by human beings which also considers various task and environmental factors. This postulation provides the rationale of a statistical model that governs the scheme of the experiment, as described below.

![Figure 1. A linkage representation composed of 4 links: torso, clavicle, right arm, and right forearm.]

In dynamic situations, a succession of instantaneous hand locations forms a trajectory which dictates the postures during a movement. Therefore, the three coordinates of hand location should be the major, albeit not the sole, determining factors. However, because of the highly redundant nature of a multi-segment posture as in the present study, the use of these three coordinates alone will not lead to a good predictive
performance. In addition to the three hand coordinates, various task and environmental factors may also affect dynamic postures significantly. It is these factors that cause postural variations even if the same hand coordinates are given; it is also these factors that represent the unknown aspects of the postural control strategy used by human beings.

Hence, the statistical model that delineates the relationship between an instantaneous posture and the determining factors can be described as follows. Let \( P_j = [\theta_{i,j}, \ldots, \theta_{i,j}]^T \) be a set of kinematic variables that mathematically describes an instantaneous posture at time \( j \). These kinematic variables could be either Cartesian coordinates or joint angles, or a combination of the two. Each variable can be modeled as

\[
\theta_{i,j} = f[X_h(t_j), Y_h(t_j), Z_h(t_j)] + g[F_1, F_2, \ldots] + \epsilon_{i,j}
\]

where \( X_h, Y_h, \) and \( Z_h \) are the three hand coordinates as functions of time, and the \( F \)'s are the hypothesized factors, such as hand motion direction, motion completion time, etc.

The symbol \( \dagger \) reflects the recognition that the relationship between \( f[\] \) and \( g[\] \) may not simply be additive. In contrast to the hand coordinates which are time-variant, the hypothesized task factors are time-invariant, and mainly categorical (e.g., time to complete a motion or movement speed, instantaneous direction, with or without handling weight and etc.). The relationship described by the above model also legitimizes an important assumption of this study. That is, across a trajectory of \( X_h(t_j), Y_h(t_j), \) and \( Z_h(t_j) \), or in its vicinity, where the movement condition formed by a specific combination of prescribed factors remains invariant, the individual kinematic variables or the overall posture can be interpolated or extrapolated. This assumption will later be referred to as the "postural continuity" assumption.

The specific hypotheses for the present experiment are: 1) hand motion direction significantly affects instantaneous posture during discrete seated reaching movement, and 2) speed mode, self-paced or motivated, used to complete movement in a slow or a fast time, significantly affects instantaneous posture during discrete seated reaching movement.
Experimental Design

A coordinate system is established to facilitate the description of the experiment. It is defined in reference to a seated person with a standard erect seating posture, with the shoulder as the origin, positive X pointing to the right, positive Y pointing to the front, and positive Z pointing up.

Three types of seated reaching tasks were incorporated in the experiment. These tasks were target-directed, with simple trajectories for hand movements. The three types differ in their directions of the hand movements, as being anterior-posterior, up-down, and medial-lateral. Figure 2 graphically illustrates how each of these three types of movements was performed:

1) the trajectories for anterior-posterior hand movements were along two directions, positive Y and positive XY (which forms a 45-deg angle with positive Y), and at two heights, chest height and waist height;

2) the trajectories for up-down hand movements were within two vertical planes, the YZ plane and the plane which bisects the YZ and XZ planes, and at two radial distances from the shoulder: 40 % and 120 % of the radius of the subjects' individual reach envelope without torso movement;

3) the trajectories for medial-lateral hand movements performed with the above two heights and radial distances.

As illustrated in Figure 2, it was intended that the hand trajectories of all the three types should intersect with each other. Eight intersections, as labeled, should result from the three types of movements, with each performed at four different locations. However, such intersections do not exist in reality because deviations from the intended hand trajectories and the jerkiness of the actual hand trajectories are inevitable during the experiment. Therefore, a "virtual intersection" was estimated as the point at which the sum of the distances to the three trajectories expected to intersect is minimal. Thus, the instantaneous postures, with the common hand position at each intersection but with
varied experimental conditions, can be interpolated or extrapolated from their corresponding measured postural profiles, based on the "postural continuity" assumption presented in the preceding section.

![Diagram of seated reaching tasks]

Figure 2. Three types of seated reaching tasks.

The point-to-point discrete reaching movements were carried out with two hand motion speeds: a self-paced, voluntary speed and a motivated, faster-than-normal speed. Three repetitions were performed. Therefore, each subject completed a total of 72 trials, the order of which was randomized. Instruction was given to keep right hand-wrist posture consistent as a pointing posture with the index finger during all the trials.

A 29 year old male student (stature: 195 cm; weight: 195 lbs) served as the subject for the pilot experiment and was paid for the participation. The subject was in good health condition. No abnormal restriction on the range of motion for any of the joint involved was reported. The intention and the procedures of the experiment were fully described to the subject. A general training secession was provided to ensure the subject acquiring a familiarity with the tasks. In addition, prior to each trial, the subject was allowed to practice the trial before he felt ready to perform the actual trial that was measured.
Data Collection and Analysis

A MacReflex motion analysis system with four digital cameras was employed to collect the motion data. A set of 6 reflective markers were placed on the body landmarks of the subjects, as depicted in Figure 3. The two ASIS (anterior superior iliac spine) markers were utilized to estimate the location of L5/S1 as their bisection. A sampling rate of 25 HZ was chosen to ensure a continuous capturing of the motions and to avoid excessive memory requirement.

![Figure 3. The body landmarks where the reflective markers were placed and the joint angles used to characterize a posture.](image)

The output from the MacReflex system is the dynamic three-dimensional coordinate data for all the markers. These data were then used to compute a set of 5 joint angles that characterize the posture of interest. These 5 joint angles are labeled in Figure 3, with their definitions listed in Table 1.
Table 1.
Joint angles defined to characterize a posture

<table>
<thead>
<tr>
<th>Angle</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Torso Flexion</td>
<td>The angle subtended by the torso link and the Y axis.</td>
</tr>
<tr>
<td>2. Torso Lateral Bend</td>
<td>The angle between the torso link and the YZ plane, with the sign</td>
</tr>
<tr>
<td></td>
<td>consistent with that of the X component.</td>
</tr>
<tr>
<td>3. Sternum Included</td>
<td>The angle subtended by the clavicle link and the torso link.</td>
</tr>
<tr>
<td>4. Shoulder Included</td>
<td>The angle subtended the upper arm link and the clavicle link.</td>
</tr>
<tr>
<td>5. Elbow Included</td>
<td>The angle subtended by the forearm link and the upper arm link.</td>
</tr>
</tbody>
</table>

Linear curve fitting was applied to obtain equations which describe the relationship between individual joint angles and the hand coordinates. These equations were then used to interpolate or extrapolate the joint angles for the eight intersection locations and under 6 experimental conditions formed by the three hand motion directions and the two hand motion speeds. These data processing procedures are summarized in a flow chart as in Figure 4. They were implemented using a Mathematica™ program created for the current investigation.

Figure 4. Data-processing procedures.

Groups of 5 joint angles, which represent instantaneous postures under the prescribed conditions, were derived by the above procedures and then used as the measures of statistical analyses. A 3×2×8 multi-variate analysis of variance (MANOVA) and subsequent tests and comparisons were conducted using Statistica™.
RESULTS

This section reports the results of a pilot experiment in which a 28 year old male subject participated. A large scale experiment involving more subjects is underway. The results are presented in three categories: effects on overall postures, effects on individual joint angles, and movement completion time.

Effects on Overall Posture

Collectively, the 5 joint angles represent the overall postural configuration of the torso and the right upper extremity. Therefore, the multi-variate analysis of variance (MANOVA) should reveal the effects of the hand motion direction and the hand motion speed on the overall posture of concern, and also how the effects may differ at the eight locations described in the previous section. Table 2 presents a summary of the MANOVA results. The results suggest that the instantaneous hand motion direction is a significant task factor (p < 0.0001) but the completion time (or the average hand motion speed) is not significant (P > 0.60).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Wilk's Lambda</th>
<th>Rao's R</th>
<th>df 1</th>
<th>df 2</th>
<th>p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3518884</td>
<td>12.61811</td>
<td>10</td>
<td>184</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2</td>
<td>0.9626514</td>
<td>0.71388</td>
<td>5</td>
<td>92</td>
<td>0.6145646</td>
</tr>
<tr>
<td>3</td>
<td>0.0017242</td>
<td>39.37337</td>
<td>35</td>
<td>389</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>1*2</td>
<td>0.9594893</td>
<td>0.38442</td>
<td>10</td>
<td>184</td>
<td>0.9523131</td>
</tr>
<tr>
<td>1*3</td>
<td>0.1133626</td>
<td>3.66179</td>
<td>70</td>
<td>442</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2*3</td>
<td>0.5867705</td>
<td>1.5034</td>
<td>35</td>
<td>389</td>
<td>0.0363087</td>
</tr>
<tr>
<td>1<em>2</em>3</td>
<td>0.4954999</td>
<td>1.00369</td>
<td>70</td>
<td>442</td>
<td>0.4743636</td>
</tr>
</tbody>
</table>
Since the hand location kinematically dictates the linkage configuration, the overall instantaneous postures at the eight locations were significantly \((p < 0.0001)\) different from each other. However, a significant two-way interaction between the direction factor and the locational factor \((P < 0.0001)\) indicates that the effect of the hand motion direction varied with respect to the hand location.

Figure 5 compares the effects of hand motion direction at the 4 locations at chest level (see Figure 2). As portrayed in Figure 5a, in the region (locations 1, 2, 5, 6) close to the body, the instantaneous postures with the same hand motion direction but different locations were more similar to each other than the ones with the same location but different hand motion direction. This was especially true for the movements with anterior-posterior (AP) hand motions. However, such a pattern did not hold for the farther region (locations 3, 4, 7, 8) where the torso assisting movements were involved in order to achieve the reach. Figure 5b illustrates that, in general, the postures were more distinctively different from each other in this region, both between the locations and between the hand motion directions. One exception to this is that the two medial-lateral (ML) motion postures at two locations were very close to each other.

At the waist level, for the closer locations (5, 6), the variations caused by the hand motion direction as well as by the location were relatively small. This is evidenced in Figure 6a where the lines are the least scattered. In contrast, for the farther locations (7, 8), there was a more distinctive difference in postures, both between the locations and between the hand motion directions.
Figure 5. Effects of hand motion direction (AP: anterior-posterior; ML: medial-lateral; UD: up-down) on overall postures at the 4 locations at chest level:
(a) at the locations 1 and 2; (b) at the locations 3 and 4.
Figure 6. Effects of hand motion direction (AP: anterior-posterior; ML: medial-lateral; UD: up-down) on overall postures at the 4 locations at waist level: (a) at the locations 5 and 6; (b) at the locations 7 and 8.
Effects on Individual Joint Angles

Variations in each individual joint angle during the tasks of different hand motions across all the locations was also investigated. This provides a different perspective and allows the effects to be examined in a more specific and detailed fashion.

(a)

Torso Flexion

(b)

Torso Lateral Bending

Figure 7. Effects of hand motion direction on torso movement across the 8 locations (see Figure 2 for locations): (a) torso flexion; (b) torso lateral bending.
Figure 7 presents a comparison of how the torso movement, including the torso flexion and lateral bending, was affected by the direction of the hand motion at different locations. It shows that there was virtually no movement, neither flexion nor lateral bending associated with the torso at the closer locations (1, 2, 5, 6). The torso flexion, as in Figure 7a, incurred by the forward torso movements was overt at the farther locations (3, 4, 7, 8), with the up-down reaching causing the most amount of flexion and anterior-posterior the least. As illustrated in Figure 7b, regardless of the hand motion direction the movement was associated with, the torso lateral bending did not occur for the closer locations, nor for the farther locations that was aligned to the YZ plane. Instead, it occurred only when the hand location was farther away and was 45 degrees from the YZ plane (4, 8).

![Sternum Included Angle](image)

**Figure 8.** The effect of hand motion direction on the sternum included angle across the 8 locations (see Figure 2 for locations).
Figure 9. The effect of hand motion direction on the shoulder included angle across the 8 locations (see Figure 2 for locations).

Figures 8 and 9 show the effects of hand motion direction on the sternum included angle and the shoulder included angle respectively. They reveal that, for the closer locations (1, 2, 5, 6), the tasks with the up-down hand motions were accompanied with smaller sternum included angle as well as smaller shoulder included angle. This means the shoulder was relatively lower and less abducted, since no torso movement was actually involved at these locations. In Figure 8, the line for the medial-lateral motions is much less 'zigzag' than the other two, which indicates the shoulder movement with respect to the torso was minimal for this particular type of movement. An additional observation is that the variation patterns for the two angles of the same hand motion direction had similar trends. In other words, at least at the same height, either chest level or waist level, the two angles with the same hand motion direction exhibited the same 'ranking order' of the joint angle magnitude for the four locations.
The effect on the elbow included angle is illustrated in Figure 10. The most salient finding regarding this angle seems to be that the arm was not fully extended (i.e., included angles less than 180 degrees), even at the farther locations where the torso movement had to be involved to complete the reach. Also of note is that, in general, the arm was less extended at the closer locations at waist level (5, 6). Furthermore, it appears that the reaching tasks with the up-down (UD) hand motions caused the elbow included angle to be smaller at the closer locations at chest level as well (1, 2), but greater at the farther locations (3, 4, 7, 8).

![Elbow Included Angle](image)

Figure 10. The effect of hand motion direction on the elbow included angle across the 8 locations (see Figure 2 for locations).

**Movement Completion Time**

Although the completion time (or the average motion speed) was identified as an insignificant factor, one question remains to be answered: Were the speeds adopted by the subject under different instructions distinctively different? Figure 11 presents the result of an analysis performed to address this question. It shows that the time to complete the movements under self-paced mode and motivated mode are significantly different, with
the former being approximately 1.5 times the latter. A further examination was made to compare the two speed modes in the current study with the existing 'normative' data in the Method-Time Measurement (MTM) system. The distance traveled by the hand in the three types of reaching tasks ranged from 50 cm to 60 cm. It appears that, the motivated speed mode was comparable to a normal B-type reach (defined as moving object to approximate location) which requires 0.68 seconds for a 50 cm distance, as predetermined by the MTM system.

Figure 11. Time to complete the movements under two speed modes.
DISCUSSIONS & CONCLUSIONS

Conceptually, there is a distinction between an instantaneous posture and a posture. An instantaneous posture is a configurational entity that carries dynamic information, such as acceleration and velocity, whereas a posture is conventionally considered as static and does not carry any dynamic information. Therefore, the dynamic information is usually not achievable in static studies, nor in movement studies analyzed in a static way. The current study has demonstrated the above distinction by the use of a collective postural measure embedded with the direction and speed information of hand motion. This facilitates the separation of the effects of hand location and hand motion characteristics on instantaneous postures, which were confounded in many previous investigations. The model created to represent these effects, as described earlier in this paper, decouples the hand locations as the kinematic variables from the hand motion direction and speed as the task factors. The hand locations kinematically dictate but do not completely determine the instantaneous postures whereas various task factors influence the way the kinematic redundancy is resolved, under different conditions evoked during various tasks. It is the latter strategic issue that is of the greatest interest to human movement and posture research.

The proposed experimental scheme is efficient in that a movement is sampled and represented by a number of instantaneous postures. This allows a quick identification of the factors that accompany and affect the postures, and avoids arduous comparisons of the entire motion profiles. One limitation of this 'sampling of a dynamic process' approach is that some aspects of a movement, such as the timing or coordination between the joints, can not be examined. However, considering the tremendous amount of data generated from a movement study, it is important to be able to compress the data and yet gain useful insights. The method presented in this study is a valuable tool; it has achieved a good compromise between efficiency and thoroughness.
The fact that the pilot experiment based on the proposed scheme yielded some results that are intuitively reasonable, together with those that are new to the current knowledge, to some extent proved the veracity of the scheme. More specifically, the use of interpolation or extrapolation to attain instantaneous postures with identical hand locations did not distort the information stored in the motion profiles. The information, which in this study was simplified by regressional descriptions of the relationship between hand (end-effector) location and the joint angle trajectories, represents the strategy of human posture control.

One of the two task factors, the movement completion time, was found to be insignificant as a result of the experiment. Most previous investigations that have addressed the completion time or the speed issue focused on arm reaching movement (Morasso, 1981; Morasso, 1983; Hogan, 1984; Flash and Hogan, 1985; Flash, 1990). Many have demonstrated the insensitivity of the movement characteristics to the speed of the movement: trajectories of hand movement during point-to-point reaching are invariant under different speed scaling (Morasso, 1981; Flash and Hogan, 1985); the velocity profile of the hand movement itself remains bell-shaped and independent of the time to complete the motion (Morasso, 1981; Soechting and Lacquinti, 1981; Kaminski and Gentile, 1986; Kaminski and Gentile, 1989). The result from this study lends support to these existing findings and strengthens the notion of speed insensitivity by expanding it to multi-segmental movement characteristics represented by instantaneous postures.

With regard to the effect of hand motion direction, there exists a correlation between the variation and the displacement magnitude. The displacement magnitude here refers to, in a collective sense, how much a posture deviates from a standard seating posture with upright torso and relaxed arms. For the eight locations studied, locations 5 and 6 caused the least deviation of the instantaneous postures; locations 1 and 2 the second least; locations 3, 4, 7, and 8 the most. The above order correlates with the order
of the variation in the postures of respective locations. The variation, caused by the effect of hand motion direction, is significant and can be as great as 20 degrees.

It is interesting to note that in the region close to the body, as the two pairs of hand locations (1 & 2, 5 & 6) at the same height were symmetric with respect to the torso axis, the instantaneous postures at the same height and with the same hand motion direction exhibited a congruency in the angles. This suggests that the axial rotation of the torso (including the horizontal rotation of the shoulder complex) may have contributed most to the variation in the postures caused by the difference in hand location, when flexion or lateral bending was not much involved. In contrast, the above congruency did not exist in general for the farther locations where the forward and lateral bending were substantial. However, while for the up-down and anterior-posterior types of motions the variations in postures are no longer attributable to the twisting of the torso, for the medial-lateral type, the postures are very similar, except that one is 45-deg axially rotated from the other. In fact, the sternum included angle for the medial-lateral type of movements did not vary significantly across the eight locations (see Figure 8), which confirms that the movement is primarily achieved by the torso axial rotation. These observations are relevant and helpful to the understanding of how different types of movements are executed, and how such understanding should be implemented in posture and movement modeling.

Examining the effects of hand motion direction on both the torso flexion and arm extension (Figure 7a, 8) reveals some information regarding the coordination between arm and torso movements. Compared to the medial-lateral or anterior-posterior reaching motion, more torso flexion was associated with the up-down motions at the farther locations, which at the same time also invoked more degrees of arm extension. During anterior-posterior motions, the least amount of torso flexion occurred and the arm was far from being fully extended. This contrast seems to suggest that when a target beyond the normal reach (reach without torso flexion) was being approached gradually, as in
anterior-posterior reaching tasks, the subject adapted and coordinated to economize the movements — unnecessary flexion or extension along the main direction (i.e., forward) was minimized; when a location beyond the normal reach had to be ballistically 'grabbed' by a forward reaching move before an up-down movement could be performed near that location, the posture was sustained in a non-optimal way in terms of eliminating excessive flexion or extension, at least along the anterior-posterior direction. The implications of the above observation are two-fold. First, it pertains to the issue of deducing the objective of an optimal strategy, if there exists any, employed by people in controlling their postural behavior. For instance, the above observation casts doubt on a joint-discomfort type cost function (Jung et al., 1994) assumed to be optimized, because it contradicts what has been observed for the up-down movements though it may not for the anterior-posterior movements. It, however, may be supportive of an energy expenditure objective function in that, for the upper-down tasks, the posture was initiated as 'non-optimal' but was somehow maintained to conserve energy expenditure, and for the anterior-posterior tasks, movements were economized as described. Second, the observation may also reflect different feedback roles played by two types of reachability judgment: a visual one used in a prompt reach to start the up-down movements, and a proprioceptive one in addition to a visual one used in a gradual forward approaching for the anterior-posterior movements. This second issue will be systematically investigated in a proposed future experiment.

It needs to be recognized that in no way are the above disclosures robust or complete. A large scale experiment will confirm, or challenge, or pose restrictions to, what has been observed and tentatively concluded in the pilot experiment. However, it is highly likely that the major findings from the current study are reproducible, and the conceptual as well as the methodological merits associated with the experimental paradigm introduced will not be depreciated.
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