Horizontal-Plane Arm Movements With Direction Reversals Performed by Normal Individuals and Individuals With Down Syndrome

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Almeida, Gil Lúcio, Daniel M. Corcos, and Ziaul Hasan. Horizontal-plane arm movements with direction reversals performed by normal individuals and individuals with Down syndrome. J Neurophysiol 84: 1949–1960, 2000. We examined the systematic variation in shoulder and elbow torque, as well as movement kinematics, for horizontal-plane arm movements with direction reversals performed by normal individuals and individuals with Down syndrome. Eight neurologically normal individuals and eight individuals with Down syndrome performed horizontal, planar reversal movements to four different target locations. The four locations of the targets were chosen such that there is a systematic increase in elbow interaction torque for each of the four different target locations. This systematic increase in interaction torque has previously been shown to lead to progressively larger movement reversal errors, and trajectories that do not show a sharp reversal of direction, for movements to and from the target in patients who have proprioceptive abnormalities. We computed joint torques at the elbow and shoulder and found a high correlation between elbow and shoulder torque for the neurologically normal subjects. The ratio of joint torques varied systematically with target location. These findings extend previously reported findings of a linear synergy between shoulder and elbow joints for a variety of point-to-point movements. There was also a correlation between elbow and shoulder torque in individuals with Down syndrome, but the magnitude of the correlation was less. The ratio of joint torques changed systematically with target direction in individuals with Down syndrome but was slightly different from the ratio observed for neurologically normal individuals. The difference in the ratio was caused by the generation of proportionately more elbow torque than shoulder torque. The fingertip path of individuals with Down syndrome showed a sharp reversal in moving toward and then away from the target. In this respect, they were similar to neurologically normal individuals but dissimilar to individuals with proprioceptive deficits. Finally, we observed that individuals with Down syndrome spend proportionately more time in the vicinity of the target than normal individuals. Collectively these results show that there is a systematic relationship between joint torques at the elbow and shoulder. This relationship is present for reversal movements and is also present in individuals with Down syndrome.

INTRODUCTION

The control of voluntary movement to different regions of the workspace requires the coordination of multiple limb segments. For example, touching one’s nose requires flexion movements of the shoulder, elbow, and wrist. The rules that describe how muscle torques are coordinated to generate such movements have not been extensively studied, although several hypotheses have been advanced for how multi-degree of freedom movements are coordinated. One hypothesis is that movement trajectories are planned in terms of the kinematic features of the movement. Support for this hypothesis comes from a series of studies that show that reaching movements have certain kinematic invariances. For example, certain types of movement have been shown to have relatively straight paths and bell-shaped velocity profiles (Morasso 1981) despite the fact that joint rotation varies considerably when movements are made to different targets. These kinematic features have been accounted for by the minimum jerk hypothesis (Flash and Hogan 1985). According to some models, muscle activation patterns and muscle torques are consequences of shifts in the equilibrium point of the limb to a target (Bizzi et al. 1984; Feldman and Levine 1995) and are not explicitly represented in the CNS.

In contrast to hypotheses that are based on kinematic properties of movements, it has also been proposed that movements are planned in terms of movement kinetics. Patterns of neural excitation are planned that produce muscle torques that generate movement (Buneo et al. 1995; Gottlieb et al. 1996a). For example, Gottlieb and colleagues have shown that there is a high linear relationship between torques at the shoulder and elbow joints when the time series of the torques at each joint are correlated. They have shown this to be the case for a variety of movements that they have studied in the vertical plane and have referred to the linear relationship between the muscle torques of two joints as “linear synergy” (Gottlieb et al. 1996a,b). A close temporal pattern for the muscle torques at the shoulder and the elbow has also been shown by Topka et al. (1998) for both normal individuals and, surprisingly, for patients with cerebellar ataxia. Gottlieb and colleagues (1997) have also shown that the ratio of joint torques differs systematically for movements to different directions. To date, however, the generalizability of the linear relationship between joint torques has not been explored for movements performed in the horizontal plane nor has it been explored in movements to and from a target (“reversal movements”).

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Individuals with Down syndrome are characterized as hypotonic, slow, and clumsy (Anson 1992; Latash 1992). Muscle hypotonia is easily recognized in the first few months of life, but no studies have related muscle hypotonia to impaired motor performance. The fact that individuals with Down syndrome are slow has been reported in a wide variety of cognitive and motor tasks, but no mechanisms have been identified that explain the reasons for movement slowness and clumsiness (Almeida et al. 2000). One possible explanation for the fact that they are clumsy is that they have abnormalities in the timing of muscle activation. Whereas neurologically normal individuals tend to activate proximal muscles prior to distal muscles (Karst and Hasan 1991), individuals with Down syndrome have much greater variability in the timing of the onset of muscle activation such that distal muscle activation often precedes proximal muscle activation (Anson and Mawston 2000). A deficit in the timing of muscle activation could lead to movements in which there is not a linear relationship between the joint torques. A second possible explanation is that they have a deficit in proprioception that could lead to movement trajectories that are abnormal when individuals are asked to make horizontal reversal movements to a target. For example, Sainburg et al. (1995) have observed that whereas in neurologically normal subjects the path to a target is virtually identical to the path back from the target when performing a reversal movement, patients with impaired proprioception exhibit consistently different paths to and from the target. Sainburg and colleagues attribute the “reversal error” made by the patients in the vicinity of the target to their inability to account for the “interaction torque” at the elbow produced by the motion of the upper arm, whose effect is particularly prominent near the reversal point. Bastian and colleagues (1996) have developed the same argument to explain why patients with cerebellar ataxia do not follow relatively straight paths when making pointing movements to a target.

To study the rules by which healthy individuals and individuals with Down syndrome make reversal movements in the horizontal plane, we analyzed a set of movements performed to four different target locations. The movements were similar to those studied by Sainburg and colleagues (1995) in that they were designed to have a similar elbow excursion but a different shoulder excursion for all four target directions; we did not, however, provide a template for the path. First, we determined whether individuals with Down syndrome would perform the movements with the same type of movement path observed for patients with impaired proprioception (Ghez et al. 1990; Sainburg et al. 1995). We hypothesized that instead of showing a sharp reversal of the path in the vicinity of the target, as neurologically normal subjects do, individuals with Down syndrome would follow a rounded path, which results from uncompensated interaction torque, as has been observed in the case of patients with impaired proprioception. If, however, a sharp reversal of the path was observed contrary to the hypothesis, this would still not rule out the possibility of uncompensated interaction torque because a nearly normal spatial path could arise from adopting an abnormal temporal pattern that reduces the interaction torque near the reversal point. Our second hypothesis tested this possibility. Based on an observation by Henderson, Morris, and Frith (1981) that individuals with Down syndrome had difficulty reversing direction when performing a sinusoidal tracking task, we hypothesized that individuals with Down syndrome would pause in the region of the target, thereby reducing the interaction torque near the reversal point. Third, we determined whether the linear relationship that has been observed between shoulder torque and elbow torque in vertical plane, point-to-point movements is observed in horizontal plane reversal movements. We hypothesized that the shoulder and elbow torque profiles would be related linearly for individuals who are neurologically normal but that the high degree of linearity would be reduced in individuals with Down syndrome.

Contrary to our first hypothesis, we found that in the vicinity of the reversal point the path to the target is quite similar to the path away from the target and is characterized by a sharp reversal in direction. Also, contrary to our second hypothesis, there was no evidence of long pauses in the region of the target although individuals with Down syndrome did take longer in the target region. In support of our third hypothesis, there is a linear relationship between shoulder torque and elbow torque in neurologically normal individuals but this relationship is weaker for individuals with Down syndrome in selected regions of the workspace.

METHODS

Subjects

Eight individuals with Down syndrome (DS) and eight neurologically normal (NN) individuals (4 males and 4 females in each group) were tested after giving informed consent according to Institutional Review Board protocols approved by the University of Illinois at Chicago. The two groups were matched by age and gender. The gender, age, weight, height, and the segment length of the upper-arm, forearm, and hand for each subject are presented in Table 1.

Apparatus and task

The subjects sat in a chair positioned close to a table. The right upper arm and forearm of the subject were positioned on the table such that the right upper arm was horizontal and facing forward (adducted horizontally by 90°) as illustrated in Fig. 1. The right forearm was flexed 90° with respect to the right upper arm as illustrated in the shaded part of Fig. 1.

In the initial position shown in Fig. 1, subjects kept their fingers extended. A metal plate was placed under their fingers at the initial position. The forearm was pronated. The wrist and the hand were immobilized with a thermoplastic splint (Aquaplast). This immobilization was necessary to match the equations used to calculate muscle torque. The trunk of the subjects was strapped in a chair to restrain movement, and the height of the chair was adjusted to keep the upper limb 10 cm above the top of the table. Even though the chair was adjusted to keep the upper limb 10 cm above the top of the table, the movement was not constrained to the horizontal plane. During the movement, the subjects had to hold their limb above the table with just the tip of the fingertip resting in the home plate. In front of the subject a target was placed in one of four different positions, all in the horizontal plane passing through the initial fingertip position. The target was made of cotton that the subjects could touch easily without any resistance. These positions were determined as follows. Four different lines were drawn through the initial starting position of the fingertip at angles of 45°. These are referred to as 135°, 90°, 45°, and 0° in Fig. 1. Along each line, the hand of the subject was passively moved by the experimenter, until the elbow extended from the initial 90° to an angle of 135°; a small rectangular target was placed at the fingertip position. Thus movements to any of the four targets required 45° of elbow excursion into extension from the initial angle of 90°.
Different target directions, however, required different amounts of shoulder excursion. We will use the terms shoulder flexion and extension as synonyms for horizontal adduction and horizontal abduction. Movements to the 135° target required shoulder flexion, movements to 90° required virtually no shoulder excursion, and movements to 45 and 0° required shoulder extension.

The subjects were instructed to position their right arm in the initial position holding the tip of the fingers in contact with the metal plate. They were then instructed to move to the target and return to the initial position "as fast as possible" on hearing a computer-generated sound along with the experimenter's command to go. As the subject's finger tip moved out of the home plate, a light was turned on at the target and stayed on until the subject had returned and touched the home plate again. Neither reaction time nor accuracy was stressed. The subjects performed movements in blocks of five trials to each target from 0 to 135°.

For the targets at 45 and 0°, the subjects were also asked to move in a time that was specified by the experimenter. The motivation for this experimental manipulation was to be able to determine whether any differences observed between individuals with DS and NN individuals were consequences of differences in movement speed. This is because it is quite possible that there is a higher correlation between shoulder torque and elbow torque for faster movements since the kinematic variables that are used to calculate the torques are larger and less influenced by noise. Subjects were instructed to move in 1.2 and 1.0 s, respectively, for the 0 and 45° target locations. For these trials, subjects were provided with movement time feedback after every trial. The feedback was based on an auditory tone that was activated when the movement was initiated and terminated when the subject reached the home plate. Subjects were told if they had reached the home plate at the correct time, too early or too late. We recorded five trials that were performed in the required movement time. Prior

### TABLE 1. Anthropometric measurements of subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Gender</th>
<th>Age, yr</th>
<th>Weight, kg</th>
<th>Height, cm</th>
<th>Segment Lengths, cm</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper arm</td>
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<tr>
<td>S1</td>
<td>NN</td>
<td>F</td>
<td>21</td>
<td>55.35</td>
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<td>50.40</td>
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<tr>
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<tr>
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<td>54.00</td>
<td>171</td>
<td>32.0</td>
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<td>33.0</td>
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<td>65.70</td>
<td>177</td>
<td>36.0</td>
</tr>
<tr>
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<td>NN</td>
<td>M</td>
<td>29</td>
<td>73.35</td>
<td>178</td>
<td>32.5</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>NN</td>
<td></td>
<td>24.3</td>
<td>61.91</td>
<td>170.8</td>
<td>1.9</td>
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<tr>
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<td>140</td>
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<tr>
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<td>DS</td>
<td>M</td>
<td>17</td>
<td>54.00</td>
<td>159</td>
<td>31.5</td>
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<td>M</td>
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<td>81.00</td>
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<tr>
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<td>DS</td>
<td>M</td>
<td>23</td>
<td>90.00</td>
<td>178</td>
<td>32.0</td>
</tr>
<tr>
<td>S16</td>
<td>DS</td>
<td>M</td>
<td>24</td>
<td>63.00</td>
<td>166</td>
<td>24.0</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>DS</td>
<td></td>
<td>23.9</td>
<td>68.97</td>
<td>156</td>
<td>28.0</td>
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<tr>
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<td>5.0</td>
<td>13.87</td>
<td>12.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Anthropometric measurements of the individuals taking part in the experiment (NN, neurologically normal; DS, individuals with Down syndrome). The upper arm length was measured from the glenohumeral joint center to the elbow joint center. The forearm length was measured from the elbow joint center to the wrist joint center. The hand length was measured from the wrist joint center to the tip of the middle finger.

Different target directions, however, required different amounts of shoulder excursion. We will use the terms shoulder flexion and extension as synonyms for horizontal adduction and horizontal abduction. Movements to the 135° target required shoulder flexion, movements to 90° required virtually no shoulder excursion, and movements to 45 and 0° required shoulder extension.

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For the targets at 45 and 0°, the subjects were also asked to move in a time that was specified by the experimenter. The motivation for this experimental manipulation was to be able to determine whether any differences observed between individuals with DS and NN individuals were consequences of differences in movement speed. This is because it is quite possible that there is a higher correlation between shoulder torque and elbow torque for faster movements since the kinematic variables that are used to calculate the torques are larger and less influenced by noise. Subjects were instructed to move in 1.2 and 1.0 s, respectively, for the 0 and 45° target locations. For these trials, subjects were provided with movement time feedback after every trial. The feedback was based on an auditory tone that was activated when the movement was initiated and terminated when the subject reached the home plate. Subjects were told if they had reached the home plate at the correct time, too early or too late. We recorded five trials that were performed in the required movement time. Prior
to data collection, subjects practiced movements in all four movement
directions. The subjects had five practice trials for each target direc-
tion performed in reverse order, from 135 to 0°. They also had three
to four practice trials for the controlled movement time experiments.

Kinematic recording and quantification

A two-camera Selsport motion-analysis system was used for kine-
matic recording. Pairs of active markers (infrared light emitting di-
odes) were fixed with tape on the upper arm and forearm aligned
along the long axis of each segment. The proximal marker on the
upper arm was placed as closely as possible to the glenohumeral joint
center. Three-dimensional position data were collected for each
marker at a rate of 200 samples/s for a duration of 2 s. From these data
the orientations of the two segments were calculated off-line. Upper
and forearm orientations with respect to the mediolateral axis (Fig. 1,
\(x\) axis) in the horizontal plane are denoted by \(\phi_x\) and \(\phi_y\), respectively,
defined as positive in the counterclockwise direction. The difference
between the two angles represents the elbow angle. The position, as
well as orientation values, were smoothed in a two-step procedure: at
each sample time, a cubic polynomial was fitted to the sample value
and the two neighboring samples on each side, and the value of the
polynomial was calculated and, subsequently, each value was re-
placed by the average over a 7-point window extending over three
adjacent points on each side. For each time derivative, the slope of the
cubic polynomial was calculated and was then smoothed over a
7-point window.

With the knowledge of the measured distance between the tip of the
middle finger and the distal marker on the forearm, the position of this
marker and the orientation of the forearm at each sample time were
used to calculate the position of the fingertip. The velocity of the
fingertip was calculated likewise from the derivatives of the marker
position and forearm orientation. Thus we could determine the path of
the tip, as well as its tangential speed, the latter being the magnitude
of the velocity. Peak tangential speed of the fingertip was determined
visually from a display using a cursor; two peak values were identi-
fied, one during the motion toward the target and the other during the
return to the initial position. The root mean square (RMS) departure
from the mean was calculated for the fingertip in the vertical (z)
direction to provide an estimate of how much motion was occurring
outside of the horizontal plane. We also calculated the time taken in
the region of the target (“target time”). The target time was calculated
from the time when the tangential speed of the finger tip dropped to
10% of its first peak to the time when it rose to 10% of the second
peak. The target time can be seen in Fig. 3A.

Kinetic computation

We estimated the inertial parameters for the proximal segment
(upper arm) and for the distal segment (forearm plus hand) on the basis
of measured values of the subject’s weight and segment lengths, using
the gender-dependent anthropometric parameters provided by Pflag-
enoef and colleagues (1983) and also cited by Kreighbaum and
Barthels (1996). The anthropometric measures provided by Pflag-
enoef and colleagues (1983) are based on NN individuals. It is well
known that the morphology of individuals with DS is different to that
of NN individuals. They tend to be heavier (Block 1991) and shorter.
However, the ratio of limb segment lengths is the same in both normal
individuals and in individuals with DS. Paired \(t\)-tests showed that
there is no difference between the two groups of individuals for the
ratio of the upper arm length to the forearm length, \(t (14) = 0.581,
P = 0.578\), and for the ratio of the upper arm length to the hand length,
\(t (14) = -1.378, P = 0.2105\). The lengths of the limb segments are
presented in Table 1.

In addition to the measured lengths of the proximal and distal
segments \((L_1\) and \(L_2\) respectively, as can be seen in Fig. 1), the
following inertial parameters were estimated: the masses of the seg-
ments \((m_1, m_2)\), the distances from the proximal end of the segment to
its center of mass \((c_1, c_2)\), and the moments of inertia about the center
of mass \((I_1, I_2)\). Given the similarity in relative segment lengths and
given that our estimates of the inertial parameters were based on
actual segment lengths, we believe that the estimates are valid for both
groups of individuals. Even if there are differences in density between
the two groups of subjects that affect the estimates of the inertial
parameters, the relative torques calculated at the shoulder and elbow
would not be affected.

At each moment of time and for each segment, given the current
coordinates of one of the markers fixed to the segment and the
orientation of the segment, the known distance of the marker from the
center of mass was used to determine the coordinates of the center of
mass. The center of mass coordinates are denoted by \((x_1, y_1, z_1)\) for
the proximal segment and \((x_2, y_2, z_2)\) for the distal segment.

The equations of motion, derived from first principles, relating the
torque at each joint to kinematic variables and inertial parameters, are
as follows. \(T_1\) and \(T_2\) represent, respectively, the “muscle” torques
(defined as positive when flexor) at the shoulder and elbow joints.

Some authors refer to this as the “generalized muscle torque (mo-
ment)” (Schneider et al. 1989, 1990)

\[
T_2 = m_e c_2 (y_2 \cos \phi_2 - x_2 \sin \phi_2) + L_2 \ddot{\phi}_2
\]

\[
T_1 = T_2 + m_e c_1 (y_1 \cos \phi_1 - x_1 \sin \phi_1)
+ m_e L_1 (y_2 \cos \phi_1 - x_2 \sin \phi_1) + I_1 \ddot{\phi}_1
\]

In deriving these equations of motion, we have not assumed that the
shoulder remains fixed in space. Note that if this assumption was
made and the center of mass coordinates was expressed in terms of
joint angles by appropriate trigonometric relations, the equations of
motion would be transformed into the more commonly employed
form in which joint angles rather than center of mass coordinates
appear as the kinematic variables.

Interaction torque was calculated as the difference between the
muscle torque at the joint and the “self torque,” the latter being the
product of the second derivative of the joint angle and the moment of
inertia of the segment about its proximal end. Using the sign conven-
tion of Sainburg et al. (1995), according to which a positive value
provides angular acceleration in the flexion direction, the interaction
torque at the elbow was defined as

\[
-T_1 - (L_1 + m_e c_2) (\ddot{\phi}_1 - \ddot{\phi}_2)
\]

To calculate the impulse of the muscle torque (i.e., its time integral)
at both the shoulder and elbow joints, we identified four time land-
marks from the muscle torque time series of each joint (Fig. 3D). The
first time \(a\) was at the beginning of the muscle torque and was
visually defined as the first sustained change from zero that started
around the onset of finger tangential speed. The second time \(b\) was
when the muscle torque crossed zero closest to the time of the first
tangential speed peak. The third time \(c\) was when the muscle torque
crossed zero closest to the time of the second peak of the finger-tip
tangential speed. The last time \(d\) was defined when the muscle
torque returned to zero around the time of the end of finger-tip
tangential speed. These times were used to divide the muscle torque
into phase I (from a to b), phase II (from b to c) and phase III (from
c to d). We then integrated the muscle torque during each of these
three phases to obtain estimates of the muscle torque impulse.

Statistical analysis

We used factorial ANOVA with repeated measures and post hoc
comparisons (Fisher’s protected least significant difference) to deter-
mine the effect of subject group and target direction on both kinematic
and kinetic parameters. We also used \(t\)-tests to determine whether
there were differences in movement time between NN individuals and
individuals with DS in the experiment in which movement time was controlled by the experimenter.

RESULTS

Individuals with DS reverse movement direction normally

The data in Fig. 2 depict the finger-tip paths for one NN individual (A) and one individual with DS (B) for movements performed as fast as possible to all four targets and then back to the initial starting position. It is important to note that at the 135° target location both groups of subjects moved toward the right of the target. Subjects did this to avoid contacting the metal plate with their thumb when the hand left the target (see Fig. 1). As such, subjects on average moved to “targets” at about 115°. All subjects displayed this constant directional error. This constant directional error does not influence our results or conclusions. Although the target was placed to restrain elbow excursion to 45° in extension at the location of each target, the path of the movement to each target was not specified.

The key point to stress about Fig. 2 is that although there are differences in the path to and from the target, there is a sharp reversal in direction for both subjects. Also, these differences are small in comparison with the differences that Sainburg et al. (1995) observed in individuals who have a proprioceptive abnormality. This was the case for all eight subjects in the two groups, and for all four target locations.

Movements of individuals with DS are slower and show more fluctuations

Figure 3 shows time-series data for kinematic variables (finger-tip tangential speed in A, shoulder and elbow excursion in B and C) as well as kinetic variables (shoulder and elbow muscle torque in D and E). The data were obtained from one movement trial to the 0° target location performed by one NN individual (broken line) and one subject with DS (solid line). The data are representative for both groups of subjects. There are both similarities and differences in the way the movements are performed by the two groups of subjects. The following similarities can be observed. The tangential speed of the finger tip exhibits two approximately bell-shaped curves, corresponding to the motions toward the target and back from the target. The angular excursions of the elbow and shoulder joint are approximately similar. Also, the shoulder and the elbow muscle torques are composed of three phases (see METHODS). Despite these similarities there are differences in the movement profiles between the two subjects. First, both peaks of tangential speed are smaller for the individual with DS, and his deceleration time for the first peak is prolonged in comparison to the acceleration time. Second, the excursion of the elbow angle is larger for the individual with DS. Third, the pattern of muscle torque has three clear phases for the NN subject, but this pattern is much less evident for the individuals with DS. Fourth, there are more fluctuations in the shape of the elbow and shoulder muscle torque profiles of the individual with DS. This is a reflection of a less smooth shoulder and elbow excursion profile and can also be observed in the finger-tip tangential speed. Fifth, the muscle torque is smaller for the individuals with DS for both joints. These differences were discernible in all eight individuals with DS.

As the target was moved from 135° to 0°, the linear distance increased. Peak tangential speed increased with respect to target location for both groups of subjects as can be seen in Fig. 4A (see Table 2 for the statistical analysis). There was an interaction between groups (NN vs. DS subjects) and target location such that NN individuals displayed a greater increase in speed with respect to changes in target location than did individuals with DS. Post hoc analysis showed that at the 135° target location the peak tangential speed was similar for both groups. Individuals with DS moved more slowly to the three other target locations than did NN individuals. Identical findings were made for the second peak of tangential speed (see Fig. 4B and Table 2), except for the 90° target location where the difference between the groups was 44.6 cm/s, but the required critical difference for statistical significance was set at 46.5 cm/s.

Individuals with DS spend more time in the region of the target

The data in Fig. 4C show the “target time,” i.e., the time spent in the region of the target, as defined in the methods section. Individuals with DS spent more time (182 ms on average) in the target region in comparison to the NN subjects (15 ms on average). There was no effect of target location on target time (see Table 2). It is important to note that at the 135° target location, despite moving at the same speed to and from the target, individuals with DS spent more time in the region of the target than did NN individuals. Therefore the longer time they spend in the region of the target is not simply a consequence of their slower movement speed. Instead there was a proportionately greater increase in deceleration time than acceleration time for individuals with DS for the movement toward the target (see Table 2). For NN individuals, the ratio of acceleration time to deceleration time was 1.08. For individuals with DS, it was 0.68. It is also important to note that if the complete movement to the 0° target is considered, NN individuals spent 47% of the time moving to the target, 3.59% of the time at the target and 49.25% of the time returning from the target. In contrast, individuals with DS spent 40.50% of the time moving to the target, 14.1% of the time at the target and 45.3% of the time returning from the target.
Shoulder and elbow torque impulses

Figure 5 depicts the averaged muscle torque impulses for the three phases of the movement at the shoulder (left) and elbow (right) joints for the DS (—) and NN (- - -) groups as functions of target location. In phase I, which corresponds to the initial part of the movement, the shoulder impulse was positive into flexion for the 135° target but was into extension for the other three target locations, whereas the initial elbow impulse was always into extension. The first muscle impulse (phase I) accelerated the limb toward the target location, and its action ended at approximately the time of the first finger-tip peak speed. The second impulse (phase II) initially decelerated the movement toward the target location and then accelerated the limb back toward the initial position. The end of the second muscle impulse was approximately around the second peak of the finger-tip speed. The third impulse (phase III) helped to brake the movement back toward the initial position. The shoulder muscle impulse during the three movement phases increased as the target changed from 135 to 0° for both groups of subjects (see ANOVA results in Table 2). There was a statistically significant interaction between subject group and target location for all three phases. Post hoc comparison showed that the shoulder impulse between NN individuals and individuals with DS differed just for the 45 and 0° target locations. Note that at the 90° target location the shoulder impulse was close to zero for both groups of individuals in all three phases.

For phases I and III, there was no significant group difference for the elbow impulse. There was a significant effect of target location and no interaction. Elbow impulse increased with target location. For phase II, there was not only a similar significant effect of target location, but there was also an interaction between group and target location showing that the elbow impulse was significantly smaller for the DS group only for the 45 and 0° target location.

Covariation of shoulder and elbow torques

We plotted the time-series data for shoulder muscle torque against elbow muscle torque and calculated the linear regression for each trial for each subject. Typical trials for a NN individual and an individual with DS are shown in Fig. 6 for movements to the 0° target. The slope obtained from this linear regression is plotted for both subject groups against the four target locations in Fig. 6B. The open symbols depict the data for the movements.
performed as fast as possible. For the 45° and 0° target locations, we also plotted the slope obtained from movements performed in an experimenter controlled movement task (as fast as possible vs. controlled movement time), target location (45 vs. 0°) and subject group (DS vs. NN) on the slope of shoulder torque versus elbow torque. The results showed that the speed instruction had no effect on the slope, \( F(1, 14) = 0.69, P = 0.42 \). There was a difference due to group, \( F(1, 14) = 15.64, P < 0.0001 \), such that the slope was larger for the NN subjects than it was for the individuals with DS. In other words, the DS subjects produced relatively less shoulder torque in relation to elbow torque, compared with the NN subjects. There was also an effect of target location \( F(1, 14) = 88.45, P < 0.001 \), such that the slope was larger for movements to 0° as opposed to 45°. None of the interactions were significant. The ANOVA results for the correlation coefficient \( r \) only showed an effect of subject group, \( F(1, 14) = 8.41, P < 0.01 \), the correlation being smaller for the individuals with DS.

At 90° there was no group difference in the slope of the regression between shoulder and elbow muscle torques, which was close to zero. At 135° the slope was negative for the NN subjects (Fig. 6B), because their shoulder and elbow muscle torques were into opposite directions (Fig. 7A), but the slope was close to zero for the DS group (Fig. 6B). This may appear to contradict the observation that at the 135° target location, there were no group difference in shoulder and elbow muscle impulse in each of the three phases (Fig. 5). The fact that the slope of the shoulder–elbow muscle torque relationship is close to zero for individuals with DS (Fig. 6B) shows that, averaged over all three phases, there is little correlation between these. This does not, however, imply that the shoulder torque did not vary in each of the three phases and therefore does not contradict the existence of nonzero impulses in the different phases. The near-zero slope for the individuals with DS for the 135° target location is consistent with the following observations. First, individuals with DS had even more fluctuation in the shoulder muscle torque profile at this target location (compare Fig. 7A with B). Second, there was more variability in the time in which the shoulder and the elbow muscle torque changed direction at this target location.

**Interaction torque**

Peak elbow interaction torque did scale systematically with target location from 135 to 0° in both groups of subjects, \( F(3, 42) = 31.54, P < 0.0001 \) as would be expected since the
targets were placed such that shoulder excursion changed systematically. There was no effect of group, \(F(1, 14) = 2.21, P = 0.16\), and there was no interaction between group and target location, \(F(3, 42) = 2.05, P = 0.121\). These data are shown in Fig. 8.

**Assumptions underlying the kinetic analysis**

The equations of motion that we present in Eqs. 1 and 2 are predicated on several considerations that can influence the validity and generalizability of the kinetic calculations. The

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**TABLE 2. Effects of subject group and target location on selected kinematic and kinetic variables**

<table>
<thead>
<tr>
<th>Variables</th>
<th>NN vs DS Group [DF (1, 14)]</th>
<th>Target Location [DF (3, 42)]</th>
<th>Interaction G vs TL [DF (3, 42)]</th>
<th>Post Hoc Comparison Fisher's Protected LSD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>First PTS</td>
<td>17.04 0.001</td>
<td>371.74 0.000</td>
<td>15.44 0.000</td>
<td>46.92 0.001</td>
</tr>
<tr>
<td>Second PTS</td>
<td>7.81 0.014</td>
<td>198.18 0.000</td>
<td>6.21 0.012</td>
<td>46.50 0.140</td>
</tr>
<tr>
<td>Target time</td>
<td>13.67 0.002</td>
<td>0.72 0.544</td>
<td>0.76 0.521</td>
<td></td>
</tr>
<tr>
<td>ACCEL. time/DECEL. time</td>
<td>27.88 0.001</td>
<td>1.94 0.154</td>
<td>0.64 0.598</td>
<td></td>
</tr>
<tr>
<td>SH. impulse phase I</td>
<td>6.10 0.026</td>
<td>104.26 0.000</td>
<td>5.48 0.002</td>
<td>0.25 0.026</td>
</tr>
<tr>
<td>SH. impulse phase II</td>
<td>5.73 0.031</td>
<td>76.48 0.000</td>
<td>5.47 0.002</td>
<td>0.55 0.031</td>
</tr>
<tr>
<td>SH. impulse phase III</td>
<td>10.57 0.005</td>
<td>17.32 0.000</td>
<td>6.01 0.001</td>
<td>0.21 0.006</td>
</tr>
<tr>
<td>EL. impulse phase 1</td>
<td>0.33 0.570</td>
<td>32.98 0.000</td>
<td>2.19 0.104</td>
<td></td>
</tr>
<tr>
<td>EL. impulse phase 2</td>
<td>4.65 0.049</td>
<td>81.04 0.000</td>
<td>8.27 0.000</td>
<td>0.34 0.049</td>
</tr>
<tr>
<td>EL. impulse phase 3</td>
<td>0.53 0.477</td>
<td>20.78 0.000</td>
<td>0.70 0.560</td>
<td></td>
</tr>
<tr>
<td>R. SH/EL IMP. phase 1</td>
<td>12.11 0.003</td>
<td>194.70 0.000</td>
<td>5.90 0.001</td>
<td>0.54 0.003</td>
</tr>
<tr>
<td>R. SH/EL IMP. phase 2</td>
<td>0.13 0.716</td>
<td>93.40 0.000</td>
<td>1.23 0.313</td>
<td></td>
</tr>
<tr>
<td>R. SH/EL IMP. phase 3</td>
<td>7.22 0.017</td>
<td>202.09 0.000</td>
<td>6.23 0.001</td>
<td>0.70 0.018</td>
</tr>
</tbody>
</table>

G, group; TL, target location; SH, shoulder; EL, elbow; PTS, peak tangential speed; R, ratio; IMP, impulse; ACCEL, acceleration; DECEL, deceleration.

* Significant at \(P < 0.05\).
first is that the so-called “muscle torque” that is calculated is due not only to muscle but is in fact the torque produced about the joint by muscles as well as passive tissues and, as such, it is influenced by any factor that affects the joint. This includes properties of tendons, ligaments and cartilage. (Differences in the properties of joints between NN individuals and those with DS are addressed in the discussion.) Second, the torque we calculate is that related to motion in the horizontal plane because it was calculated only about the vertical axis. We investigated motion in the vertical plane. We found no statistically significant difference between the two groups in the RMS value of the fingertip motion in the vertical plane, $F(1, 14) = 5.09, P = 0.035$. There was no statistical significant effect of target orientation, $F(3, 42) = 10.9, P < 0.0001$. There was greater vertical motion for the target at 0° (Fisher’s protected least significant test) than the other three locations but this motion only amounted to 1.8 cm. There was no interaction between subject group and target location, $F(3, 42) = 1.56$, $P = 0.21$. Third, because our estimates of the inertial parameters are based on cadaver data obtained from NN individuals, our estimates of the torque magnitudes could be in error if the inertial parameters were significantly different for individuals with DS. We know of no reason to believe, however, that the relative masses of the forearm and upper arm segments, for example, are different in individuals with DS compared with individuals who are NN. Therefore the relative torques at the two joints, and thus the slope relating them, should not be in error for the DS individuals. Fourth we splinted the wrist and hand, asked subjects to keep their arms above the table and did not allow any impact with the target so that the equations of motion would not be compromised by unaccounted for joint motion, friction and impact.

**DISCUSSION**

The data we have presented extend previous findings of a linear relationship between elbow torque and shoulder torque to horizontal, planar reversal movements. The strength of this linear synergy is less in individuals with DS, and the slope of the relationship between elbow torque and shoulder torque is also different in individuals with DS for some target directions. The data also show that individuals with DS spend more time in the vicinity of the target. Finally, we found that the hand path of individuals with DS is similar to and from the target in the vicinity of the reversal point. We will discuss each of these issues in turn.

**Linear synergy in reversal movements**

As has previously been reported, we also find that the dynamic muscle torques of horizontal, reversal movements are triphasic (Gottlieb 1998; Sainburg et al. 1995; Schmidt et al. 1988; Sherwood et al. 1988). The first muscle impulse accelerates the limb toward the target location. The second impulse initially decelerates the movement toward the target location and then accelerates the limb back toward the initial position.
The third impulse terminates the movement at the initial position. The elbow and shoulder muscle torques that generate these impulses are qualitatively very similar and are closely synchronized temporally in NN individuals.

Gottlieb and colleagues (1996a) have shown that in normal subjects the shoulder and elbow torques follow a coordination rule, termed "linear synergy," for the performance of a variety of different movements. The CNS sends a common temporal pattern to activate the muscles of the two joints, leading to muscle torque profiles of similar shapes at each joint. These muscle torques are then scaled in amplitude to the demands of the task. In other words, the elbow and shoulder muscle torques are related by a scaling constant. They pass through extremes and zero crossings almost simultaneously for a variety of different movements as has also been shown by Topka et al. (1998). When an individual is explicitly instructed to use an unusual hand-path, the linear synergy rule does not apply (Gottlieb et al. 1996a), and therefore this rule is not an obligatory feature of the mechanics of the movement. This linear synergy between muscle torques can be found in sagittal planar movements during pointing (Gottlieb et al. 1996a), reaching movements in different directions (Gottlieb et al. 1997) and in the data reported by Bock (1994) and Buneo and colleagues (1995).

In the present data set, we show that linear synergy is also observed for unconstrained horizontal plane reversal movements, which require the coordination of elbow and shoulder torques. The ratio between the torques varies with target location as shown for pointing movements performed against gravity in the sagittal plane (Gottlieb et al. 1997). We also confirm the observation of Gottlieb and colleagues (1996b) that the ratio of the muscle torques does not depend on movement speed. When the subjects were asked to move to the 45 or 0° target locations at different speeds, they used the same ratio between elbow and shoulder muscle torque independently of speed (Fig. 6B).

We found that, in general, both NN individuals and individuals with DS use linear synergy to perform reversal movements. However, there were subtle differences in the generation of shoulder and elbow torques by DS individuals that may account for certain differences in their movement performance. One such difference is that there is more fluctuation in the muscle torque for the movements of DS individuals (Figs. 3, D and E, and 7B). This decrement in the smoothness of the movements of individuals with DS may well explain the reduction in the strength of the linear relationship between elbow and shoulder torque observed in the individuals with DS. The ratio of the torques determines movement direction, whereas the magnitude of the torques determines movement speed. We will now address the question of how differences in the magnitude and ratio of the torques can explain the characteristics of the movements of individuals with DS.

**Movement trajectory**

We observed no major differences in the trajectories of the individuals with DS in comparison with the NN individuals. They made movements both to and from the target following a similar path to that of the NN individuals (Fig. 2). This is in sharp contrast to the movements described for deafferented subjects in which the movement path to and from the target was very different, especially in the vicinity of the reversal point, despite the fact that, unlike in our study, the subjects were given a straight line to follow (Sainburg et al. 1995). As such the data do not support our first hypothesis that individuals with DS may exhibit a pronounced difference in movement paths during reversal of movement akin to what has been reported for individuals with impaired proprioception.

The argument has been made that certain neurological deficits may give rise to an inability to "control interaction torque" (Bastian et al. 1996; Sainburg et al. 1995). The rationale for this argument is based on the assumption that individuals with a loss of proprioception or with a lesion of the cerebellum do not have an appropriate model of limb dynamics to account for interaction torques using a feedforward mechanism. In our
Movement planning, as in that of Sainburg and colleagues (1995), the magnitude of peak interaction torque at the elbow systematically increased with targets requiring greater shoulder extension. As such, if individuals with DS did not have an appropriate model of limb dynamics, the reversal of movement in the vicinity of the 0° target, when the interaction torque is greatest, should have exhibited a rounded path rather than a sharp turnaround. It did not. We failed to identify any kind of pattern for the interaction torque that discriminated between normal individuals and the individuals with DS.

Movement speed and target time

As has been observed in several previous studies (Almeida et al. 1994; Aruin and Almeida 1997; Aruin et al. 1996), the movements of individuals with DS are slower when compared with NN subjects [cf. a review by Anson (1992)]. They move slowly because they generate smaller muscle torques. The only exception was for the 135° target location (Fig. 4). At this target location, the muscle torque impulses were comparable across groups and so was the movement speed (Fig. 4, A and B). Note that even though elbow and shoulder muscle torques were not temporally correlated for the 135° target location for the individuals with DS (Fig. 7B), the magnitude of the torque impulses were similar across subject groups (Fig. 5).

The time in the vicinity of the target was disproportionately longer for individuals with DS for all target locations (Fig. 4C). This longer time in the target region is consistent with a study by Henderson et al. (1981) in which children with DS were asked to track a moving sinusoidal template. The children with DS could track the sine wave quite well when the movement was slow and even draw it from memory on stationary paper. However, they failed to track the moving sinusoidal template when it moved quickly, especially as it reversed direction. They made a series of straight, discrete movements instead. A pause separating the movements to and from the point of reversal would also seem consistent with an attempt to reduce the interaction torque, which would otherwise impart an unwanted motion to the elbow. Based on these considerations, we had hypothesized that to produce a sharp reversal in the spatial path, individuals with DS would move to the target, stop, and then return. In other words, they would perform the task as two discrete movements. This was clearly not the case because if they had paused at the target location, their finger-tip speed would have remained zero during the target time, and this is not what we observed (Fig. 3). This observation rules out the possibility that they could have forgotten for a brief time to return to the initial position and therefore treated the reversal movement as two separate movements. This is because simple reaction time has been reported to be 150 ms for control subjects and more than 300 ms for individuals with DS (Berson and Baumeister 1967). The average target time for the individuals with DS was around 182 ms, which is considerably less than the time one would expect if the return movement was a new movement. Furthermore the longer reversal time for the DS subjects did not result in an appreciable reduction in the peak interaction torque (Fig. 8), which contradicts the idea that the altered temporal pattern exhibited by DS subjects is an adaptation for an inability to account for interaction torques in movement planning.

The increased time in the vicinity of the target (Fig. 4C) also cannot be attributed to differences in movement speed between the two groups of subjects. This is because at the 135° target location both groups of individuals moved at comparable speeds but the time in the vicinity of the target of the individuals with DS was about 150 ms longer. The longer time in the vicinity of the target can be attributed, in part, to a prolongation of the deceleration phase toward the target, which we observed. Although Almeida and colleagues (1994) have shown that DS individuals exhibit symmetry between the acceleration and deceleration phases for elbow flexion movements, the symmetry may be compromised in the case of reversal movements. Alternatively, it may be the case that deceleration time may be prolonged in individuals with DS for movements that require close monitoring of visual feedback. Charlton, Insen, and Lavelle (2000) have also shown that individuals with DS spend more time in the vicinity of the target that are observed between the two groups of individuals.

Neurobiological basis of motor difficulties in DS

The results that we have presented are important for two reasons. On the one hand, they suggest that linear synergy is a fundamental feature of the control of movement that is not degraded even in the presence of a genetically abnormal sensorimotor, musculo-skeletal system (Chiarenza and Stagi 2000). On the other hand, the neurological and biomechanical differences in individuals with DS may well explain the differences in movement speed and time spent in the region of the target that are observed between the two groups of individuals. For example, pyramidal cell abnormalities have been identified in the motor cortex of a child with DS (Marin-Padilla 1976), and the weight of the cerebellum has been reported to be reduced (Crome et al. 1966). In addition, there is evidence of axonal degeneration from the study of peripheral and CNS conduction parameters (Mackenzie et al. 1983). Individuals with DS may also have differences in bone density and cartilage hypoplasia and possibly alterations in the biomechanical properties of ligaments, although the evidence for differences in the biomechanical properties of ligaments has been questioned (Cremers and Beijer 1993; Stein et al. 1991). These differences might influence the ability to generate joint torque, especially since individuals with DS do generate reduced levels of force when generating isokinetic contractions (Cioni et al. 1994). It is also possible that differences in movement speed and time spent in the region of the target are indirect consequences of mental retardation and not due to the above-mentioned reasons. Future studies are required that use a control group matched for differences in intelligence to determine whether the differences that we have documented are due to altered central processing or due to alterations in the sensorimotor system.

Conclusion

The results that we have presented show that linear synergy occurs in horizontal plane reversal movements to a target. These results confirm and extend previous findings concerning the linear relationship between joint torques. Linear synergy also occurs in individuals with DS. They do have the ability to
specify different ratios of torques at the shoulder and elbow joints to move to selected targets, although they do generate more elbow torque in relation to the shoulder torque as compared with NN individuals. The movement path, however, is sufficiently similar to that of normals to suggest that their abnormality is not akin to the abnormality observed in patients with proprioceptive deficits. Individuals with DS differ from normal individuals mainly in that they produce less muscle force, and thus their movements are slower, but they slow down in the vicinity of a reversal point disproportionately more than what may be expected on the basis of their lower speed. This somewhat altered speed profile, however, does not result in an appreciable reduction in the peak interaction torque. In addition, their muscle torque profiles show greater fluctuations. The results suggest that future research on the motor ability of individuals with DS should focus on the precise timing and sequencing of muscle activation for movements in different directions.

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