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# Evidence of Motor Equivalence in a Pointing Task Involving Locomotion

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A pointing task was performed both while subjects stood beside and while subjects walked past targets that involved differing movement amplitudes and differing sizes. The hand kinematics were considered relative both to a fixed frame of reference in the movement environment (end effector kinematics) and to the subject's body (kinematics of the hand alone). From the former view, there were few differences between standing and walking versions of the task, indicating similarity of the kinematics of the hand. However, when the hand was considered alone, marked differences in the kinematics and spatial trajectories between standing and walking were achieved. Furthermore, kinematic analyses of the trunk showed that subjects used differing amounts of both flexion-extension and rotation movements at the waist depending on whether they were standing or walking as well as on the constraints imposed by target width and movement amplitude. The present results demonstrate the existence of motor equivalence in a combined upper and lower extremity task and that this motor equivalence is a control strategy to cope with increasing task demands. Given the complexity involved in controlling the arm, the torso, and the legs (during locomotion), the movements involved in the present tasks appear to be planned and controlled by considering the whole body as a single unit.

***Key Words***: pointing, locomotion, prehension, posture

Traditional manual aiming and prehension research utilizes paradigms that unnaturally constrain the subject and decrease the potential degrees of freedom available to the subject while performing the movement. This research also tends to focus on control of the arm and hand only, ignoring any other body movements or postural actions associated with natural reaching movements. Recent work has attempted to include postural contributions to aiming and prehension movements and the results have suggested that control of the trunk is tightly integrated with, and perhaps inseparable from, the control of the arm (Kaminski, Bock, & Gentile, 1995; Saling, Stelmach, Mescheriakov, & Berger, 1996; Steenbergen, Marteniuk, & Kalbfleisch, 1995).

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This should not be surprising as it is well established that muscle activity in the prime movers of voluntary upper limb movements is preceded by activity in postural muscles to counteract the resulting shift in the body's center of mass, prompting some to suggest that these anticipatory postural responses can be seen as part of the planned voluntary response (e.g., Lee, 1980; Vernazza, Cincera, Pedotti, & Massion, 1996; Weeks & Wallace, 1992). Considering the upper limb movement and its postural requirements, it can therefore be suggested that any voluntary movement could potentially involve coordinated activity in muscles throughout the body.

The goal of the present research was to determine if the degrees of freedom normally associated with posture and/or locomotion assumed an integral role in contributing to the control of the end effector in a pointing task. To that end, a pointing task was performed both while subjects stood beside, and while subjects walked past targets. This paradigm bridges the gap between two recent lines of investigation. First, a number of studies have investigated trunk assisted reaching. In these studies, subjects are forced to flex at the waist from the seated position to reach targets that are beyond arm's length. Results from these studies have suggested that the pointing limb is controlled at the end point, with the contributions of the arm and trunk to the transport of the hand (end effector) being largely complimentary, to produce consistent trajectories of the hand to the desired end point (Kaminski et al., 1995; Ma & Feldman, 1995; Saling et al., 1996). In addition, Saling et al. (1996) reported invariant trunk contributions despite changes in the task constraints. These authors reported virtually no effects on trunk kinematics, while end effector kinematics reflected precision effects based on object size. Conversely, Steenbergen et al. (1995) showed that the contribution of the trunk in a prehension task was greater when picking up a cup full of liquid versus an empty cup. Though somewhat contradictory to earlier findings, the results of Steenbergen et al. (1995) suggest two important hypotheses for the present work. The first is that the motor control system is capable of employing additional degrees of freedom to aid in the successful completion of a task. This ability to achieve an invariant end using variable means has been termed motor equivalence (Abbs & Cole, 1987). The second and perhaps more interesting hypothesis is related to the apparent contradiction between the works of Saling et al. (1996) and Steenbergen et al. (1995). The results of the former study showed that trunk motion remained constant when reaching for objects, whereas the results of the latter work revealed that in certain instances, the trunk did in fact supplement the reaching movement. Because Saling and his colleagues (1996) had subjects reaching for one of two dowels that were quite similar in dimensions, it is possible that the task was not complex enough to allow for the full expression of the coordination system. Therefore, as one aspect of the present study, we propose that motor equivalence may appear to a greater extent as the difficulty of the task increases.

The second line of research that is of interest to the paradigm used in the present study is that which combines an upper limb task with locomotion. This work tends to focus more on the coordination of the upper and lower limbs (e.g., Carnahan, McFadyen, Cockell, & Halverson, 1996; Muzii, Lamm Warburg, & Gentile, 1984). These studies indicated that the locomotion movements were resistant to the performance rate of upper limb tasks (Muzii et al., 1984) and precision effects of grasping tasks (Carnahan et al., 1996). These results would seem to suggest that any adjustments required to accommodate task constraints could be made at the level of the hand. It is noteworthy, however, that similar to Saling et al. (1996), Caranhan and her colleagues (1996) employed a big dowel/little dowel paradigm. It is therefore possible that once again, the lack of findings in the lower limbs may be due to the simplicity of the task.

For the purposes of the current study, we integrated elements of trunk-assisted reaching research with elements of combined upper and lower extremity research. In addition, we employed a task with increasingly difficult conditions to determine if adding task complexity alters the coordination strategy. Our objective was to determine the extent to which coordination of the upper limb system with the postural and locomotion systems would occur in a task of varying complexity. At the same time we wished to determine the extent to which motor equivalence might be a response to increasing task difficulty.

## Method

### *Subjects*

Seven male subjects (mean age: 21.6 years) participated in this experiment after providing informed consent. All subjects were right handed, had normal or corrected-to-normal vision, and no history of neuromotor deficits. Subjects received an honorarium of $20 for participating in a single experimental session.

### *Apparatus*

Kinematic data were collected using an OPTOTRAK 3010 camera system (Northern Digital, Waterloo, Ontario). Four infrared emitting diodes (IREDs) were placed on the subject. One IRED was placed on the middle segment of the subject's right index finger and was used for determining the kinematics of the end effector for the pointing movement. Three IREDs were placed on an elastic strap that was placed around the subject's torso. These three IREDs, centered approximately 10 cm inferior to the subject's xyphoid process, were used to determine the movement of the upper body during the trial.

Two channels of analog data were also collected using the OPTOTRAK Data Acquisition Unit. The signals for the analog channels originated from contact between the stylus and two separate target plates. The first target plate was 100 mm by 100 mm square. The second target was one of a set of three round targets, with diameters of 10, 20, and 40 mm. Contact between the stylus and a target plate caused a change in voltage output from 0 to 5 V to occur. It was this change in voltage that was collected and used to determine the start and end of the movement. These targets were placed on an adjustable platform that allowed the standardization of the target height to the height from the floor of the most distal aspect of the humerus while the subject stood erect. Both the kinematic and analog data were collected at a sampling rate of 200 Hz.

### *Procedures*

Subjects read an information sheet that explained the experimental procedures and indicated that the experiment had been approved by Simon Fraser University's Ethics Committee, and then signed an informed consent form. Subjects were instrumented with the IREDs and given the stylus. Subjects were instructed to hold the stylus as they would a pen, and to use the tip of it to tap the targets, as closely as possible to the target's center. The targets were placed on a table to the subjects right, with the height of the targets adjusted to approximately match 90° of elbow flexion for each subject. The pointing movement was to be performed as quickly and as accurately as possible.

In general, this pointing task involved having subjects tap an initial target, then quickly tap a second target placed at a distance anterior to the first. The second target was experimentally manipulated both in terms of its size, and distance from the first target. Subjects were given a few moments to familiarize themselves with walking and moving their arms while instrumented prior to beginning the testing session. The experiment was comprised of two conditions: (a) standing and pointing, and (b) walking and pointing. The first target was very large and required very little precision in comparison to any of the second targets. The movement of interest was defined as starting at the time of initial contact with Target 1, and ending at the time of initial contact with Target 2. Thus, the task was essentially a sequential pointing task, with only the movement between the targets analyzed. One condition involved performing 108 trials (3 amplitudes × 3 target widths × 12 trials) of pointing to both targets while standing still (i.e., no locomotion but with the auditory metronome present). The other condition involved pointing to both targets while performing 108 externally paced walking trials. Prior to beginning the walking condition, subjects were allowed to practice walking to an auditory metronome set to approximately 1.75 Hz. Subjects were instructed to time heelstrike to coincide with the metronome pulse. Heelstrike was chosen as the anchor event because it has been shown that subjects naturally choose to couple heelstrike with a metronome (Mauerberg & Adrian, 1995). The step rate was chosen based on the overall average natural step rate reported by Winter (1989) of 1.78 Hz. The walking condition involved essentially the same sequential pointing task as described earlier, however in this case, subjects performed the movement while walking alongside the table supporting the targets. Subjects were instructed not to make multiple attempts to successfully hit the target but to try to hit the target on the first try. In either condition, if a subject failed to hit any of the targets, that trial was immediately repeated. In addition, subjects were instructed not to step forward (standing condition) nor interrupt the heel-metronome rhythm (walking condition) during a trial.

The distance between the targets (amplitude) and the diameter of the second target (width) were pseudorandomly varied from trial to trial within the two conditions. Values of amplitude were 15, 30, and 60 cm, as measured from the centers of the targets. Target width varied from 10 to 20 to 40 mm.

Three subjects performed pointing while walking followed by pointing while standing, while the other 4 performed these sets of trials in the opposite order. The experiment was approximately 2 hrs in duration and was performed in one session.

### Data Treatment

Only trials in which subjects successfully completed the required pointing task (i.e., hit each target on the first attempt) were considered for analyses. In addition, trials with missing frames of data (e.g., due to IRED occlusion) were interpolated to fill in gaps of less than or equal to 20 ms. Files with larger gaps were discarded.

The data were filtered once using a low-pass frequency of 6 Hz with a Butterworth dual-pass filter. Pointing kinematics were analyzed to determine the characteristics of the pointing movement. Four kinematic measures were considered: magnitude of peak velocity, time to peak velocity, time after peak velocity, and time after peak velocity as a percent of movement time. The interval between target contacts defined movement time (MT). The movement kinematics were considered relative to both a fixed frame of reference in the movement environment and to the subject's body (as defined by the three torso IREDs). To determine the movement of the hand with respect to the body as a dynamic frame of reference, the movement of the torso in three dimensions was subtracted from the movement of the hand in three dimensions. This allowed the determination of the extent to which the body movement contributed to the end effector's (i.e., the hand and stylus) movement. The torso IREDs were also used to calculate torso angles in the sagittal (trunk flexion-extension) and transverse (trunk rotation) planes. In addition, consistency of position of the hand IRED was determined by calculating the standard deviation (*SD*) of the IRED position in both the X (the forward axis of the movement) and Y (the side to side component of the movement) dimensions at time of contact with Target 1 and Target 2. Finally, total displacement in the X dimension was calculated by the difference in IRED position from the start to the end of the movement, as defined by target contacts.

All dependent measures were submitted to a 2 Condition (standing and walking) × 3 Amplitudes (15 cm, 30 cm, and 60 cm) × 3 Widths (10, 20, 40 mm) ANOVA with repeated measures on all factors using BMDP 8v.

## Results

For the purpose of this report we focused on the results pertaining to the differences between the standing and walking conditions. Our main interest was the differences in performance and control of the pointing movement under these two conditions. In addition, the high level interactions, when they occur, are considered at the expense of the main effects. These main effects are discussed only as they aid in the explanation of the significant interaction.

### *Consistency of Hand Position at Time of Target Contact*

Consistency of hand position at the time of target contact was considered in the plane of the target, yielding an X (forward, sagittal) dimension and Y (side to side, frontal) dimension component to the hand's position, which were analyzed separately. These data are displayed in Table 1 as the condition means separately for *SD* in the X and Y dimensions for Target 1, and as the means for the condition by width interaction for Target 2.

*Target 1.* There were no condition effects for hand position at time of contact with Target 1 in either axis. Neither mean within subject *SD* in the X dimension, $F(1, 6) = 1.17$, nor mean within subject *SD* in the Y dimension, $F(1, 6) = 2.78$, yielded effects for condition. Thus, consistency of hand position at Target 1 contact was not affected by whether the subject was walking or standing.

**Table 1 End Effector Spatial Variability at Time of Contact with Target 1 and Target 2—Mean Within Subject Standard Deviations (cm) of Position in the X (Antero-Posterior) and Y (Lateral) Axes as a Function of Condition and Width**

| | *SD* X | | *SD* Y | |
|---|---|---|---|---|
| Target | Stand | Walk | Stand | Walk |
| Target 1 | 0.99 | 1.15 | 1.07 | 0.82 |
| Target 2 | | | | |
| 10 (mm) | 0.78 | 0.68 | 0.67 | 0.78 |
| 20 (mm) | 0.92 | 0.79 | 0.78 | 0.67 |
| 40 (mm) | 0.91 | 0.89 | 0.73 | 0.81 |

*Target 2.* Variability of hand position at time of Target 2 contact increased in the X dimension as width increased, $F(2, 12) = 4.16$, $p < .05$, although this increase was not as large as might have been anticipated based on the four-fold increase in target diameter: 7.3 mm, 8.5 mm, and 9.0 mm for the 10 mm, 20 mm, and 40 mm target diameters, respectively. In the Y dimension a marginally significant Condition × Width interaction was found, $F(2, 12) = 4.02$, $p \approx .05$. However, this appears to be a spurious result, as the two extreme means occur for the 20 mm and 40 mm targets diameters in the walking condition. Thus increasing the diameter of Target 2 had a small effect on hand position along the X dimension that could not be directly scaled to target diameter. Importantly, no meaningful effects involving condition were found, suggesting a similar level of task performance between the standing and walking conditions.

## *Total Displacement of Hand*

Total displacement in the X dimension was determined from time of Target 1 contact to time of Target 2 contact. Predictably, a main effect for amplitude was found, $F(2, 12) = 25{,}205$, $p < .0001$, indicating that as amplitude increased, hand displacement while pointing increased. The mean displacements for each ampli-

**Table 2 Mean and Mean Within Subject *SD* of Total Displacement (cm) of End Effector from Contact With Target 1 to Contact With Target 2 as a Function of Condition and Width**

| | Displacement | | | |
|---|---|---|---|---|
| | Mean | | *SD* | |
| Width (mm) | Stand | Walk | Stand | Walk |
| 10 | 33.1 | 34.2 | 1.01 | 1.10 |
| 20 | 33.0 | 34.6 | 1.04 | 1.19 |
| 40 | 32.5 | 34.7 | 1.14 | 1.21 |

tude (14.0 cm, 28.7 cm, and 58.4 cm) indicate an overall tendency to undershoot the actual distance between the targets measured from the center of Target 1 to the center of Target 2. A significant Condition × Width interaction was also found, $F(2, 12) = 4.38$, $p < .05$. This interaction resulted from a tendency for the movement to be performed with greater displacement in the X dimension in the walking condition (34.5 cm) compared to the standing condition (32.9 cm), $F(1, 6) = 31.53$, $p < .002$ for the main effect of condition. In addition, the difference between the mean displacements for the walking and standing conditions became greater as target diameter increased. No differences were found for the mean within subject *SD* of hand displacement, indicating no effects of variability in total hand displacement. The data for the Condition × Width interaction are displayed in Table 2, along with the nonsignificant Condition × Width data for mean within-subject *SD*.

## *Kinematics: Movement Time (MT)*

A 2 Condition × 3 Amplitude × 3 Width ANOVA with repeated measures on all factors indicated the similarity of the movements when considering the mean MT results involving the factor condition (e.g., mean MT was 414.8 ms in the standing condition and 428.9 ms in the walking condition).

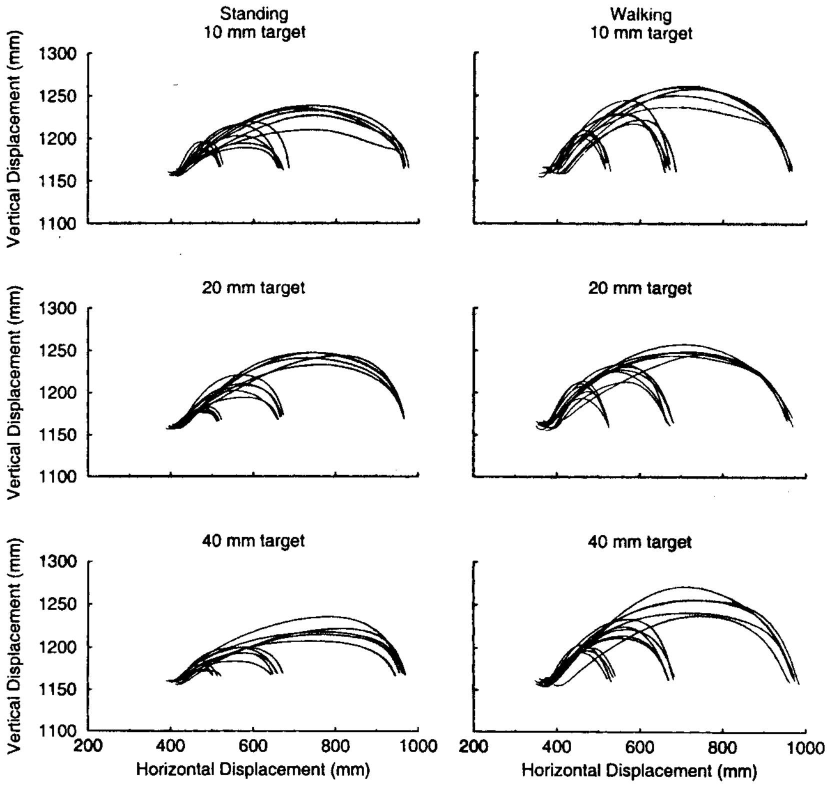
## *Kinematics: End Effector*

The hand IRED was used to characterize the movement of the end effector (hand plus stylus) in space. In this context, the movement of this IRED represents the movement of the end effector without regard to what body movements are contributing nor how they contributed to the overall movement.

Initial observations of the data indicated that the tangential velocity of the hand IRED was double-peaked, one early on in the movement and the other at about 50% of the movement duration. We speculated that this double-peaked tangential velocity was a result of the sequential nature of this task, where the subject was required to first hit the initiating "target" and then move on to hit the second target. The first peak would be the result of coming up quickly, not unlike bouncing, from the first target and thus producing an early and large peak in the vertical (Z) dimension, while the second peak would be associated with the velocity in the forward (X) dimension later on in the movement. To confirm that this was indeed the case, and the double-peaks were not due to the standing and/or walking conditions, we used seated subjects for the same task and again found the double-peaked tangential velocities. For this reason the velocity-related kinematics of the movement were separated into the X and Z dimensions and analyzed separately.

*Spatial Path Plots.* Figure 1 illustrates the spatial path of the hand IRED for 2 different subjects in the X (forward) and Z (vertical) dimensions. These 2 subjects demonstrate the two different spatial paths that were seen. Specifically, some subjects consistently performed the movement with qualitatively similar bell-shaped trajectories in walking and standing (Figure 1a), while others consistently performed the movement with a low altitude, more rectangular movement when pointing while walking (Figure 1b). Regardless of the shape of the trajectory, the movements within a condition to a given amplitude-width combination were always performed with consistency of trajectory shape.

FIGURE 1A




*The Movement in the X Dimension.* Peak velocity in the X dimension (PV-X) yielded a significant Condition × Amplitude interaction, $F(2, 12) = 15.7$, $p < .001$. PV-X increased with amplitude, but it increased at a higher rate in the standing condition compared to the walking condition. However, as indicated previously, this PV-X effect did not manifest itself as a difference in MT.

None of the temporal measures associated with PV-X yielded effects involving condition: in absolute time and relative to MT, the times to and after PV-X were equivalent regardless of whether the pointing movement was performed while the subjects were walking or standing. The data for the kinematic measures in the X dimension are displayed in Table 3.

*The Movement in the Z Dimension.* A condition by amplitude interaction, $F(2, 12) = 17.7$, $p < .0005$, was found for peak lifting velocity (PV-Z). PV-Z increased with amplitude: 468.8 mm/s, 545.2 mm/s, and 644.7 mm/s for the 15, 30, and 60 cm target amplitudes, $F(2, 12) = 151.8$, $p < .0001$ for the main effect of amplitude. This amplitude effect influenced PV-Z to a greater degree in the standing condition compared to the walking condition.

A Condition × Amplitude interaction, $F(2, 12) = 6.6$, $p < .05$, was also found for time to PV-Z. The significant amplitude main effect, $F(2, 12) = 29.8$, $p < .0001$, in which time to PV-Z increased with amplitude, was greater in the

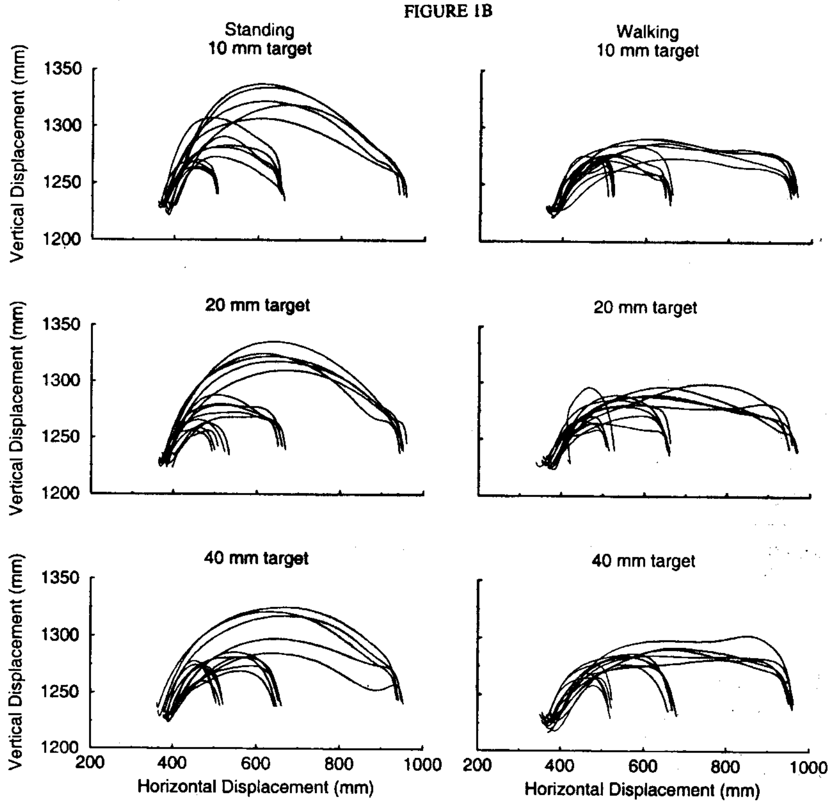



**Figure 1 — Spatial plots involving the forward or horizontal and the vertical displacements of the hand viewed from a fixed, room centered, frame of reference. Figure 1A shows five trials and their spatial paths for 1 subject for each of the conditions involving some combination of standing; walking; target sizes of 10, 20, and 40 mm; and movement amplitudes of 15, 30, and 60 cm. Figure 1B shows the spatial paths of a second subject.**

standing condition compared to the walking condition, accounting for the significant interaction. None of the remaining two temporal measures associated with PV-Z resulted in any condition effects. These data are also displayed in Table 3.

Thus it is apparent that the end effector kinematic and accuracy measures of the pointing movement suggest similarity of the movements regardless as to whether they were performed while standing or walking.

## *Kinematics: Hand With Body as Frame of Reference*

These analyses consider the movement of the hand relative to the body as a dynamic frame of reference. The same analyses that were carried out for the end effector were carried out on these data. Of note here is the finding that the net

**Table 3 Kinematic Characteristics of the End Effector During the Pointing Movement in the X (Antero-Posterior) and Z (Vertical) Dimensions Using a Fixed, Room-Centered, Frame of Reference**

| Dimension/ amplitude (cm) | Peak velocity[a,b] (mm/s) | | Time to velocity[b] (ms) | | Time after peak velocity (ms) | | Time after peak velocity (% MT) | |
|---|---|---|---|---|---|---|---|---|
| | Stand | Walk | Stand | Walk | Stand | Walk | Stand | Walk |
| X | | | | | | | | |
| 15 | 768 | 767 | 171 | 180 | 123 | 138 | 40.6 | 41.8 |
| 30 | 1279 | 1190 | 203 | 200 | 188 | 204 | 46.6 | 49.4 |
| 60 | 1989 | 1752 | 244 | 257 | 317 | 306 | 55.0 | 53.9 |
| Z | | | | | | | | |
| 15 | 450 | 488 | 97 | 96 | 196 | 223 | 65.6 | 69.1 |
| 30 | 553 | 538 | 106 | 101 | 284 | 304 | 71.8 | 74.5 |
| 60 | 706 | 584 | 116 | 106 | 444 | 457 | 78.4 | 80.9 |

[a]Significant Condition × Amplitude interaction for PV-X; [b]Significant Condition × Amplitude interaction for PV-Z.

displacement of the hand from Target 1 to Target 2 was consistently towards the body in the walking condition. This is in stark contrast to what can be considered normal pointing that is seen in the standing condition, where the hand contacts Target 1 then moves away from the body and towards Target 2.

*Spatial Path Plots.* Figure 2 displays the spatial path of the hand IRED relative to the subject's torso. The left half of the figure displays the trajectories of the hand for the standing condition. These trajectories are not dissimilar from those shown in Figure 1, except for the end of the movement. As subjects had to lean forward (flexion at the waist) to reach the farther targets, the frame of reference to which the hand IRED was compared moved downwards. This caused the hand to be higher compared to the torso when Target 2 was contacted than it was when Target 1 was contacted.

The right half of Figure 2, where representative trials from the walking condition are presented, is also interesting. Consider the 15-cm amplitude pointing movements. These trajectories tend to be skewed bell shapes. In these cases the hand contacts Target 1 then moves towards the body (from right to left in the figure) to hit Target 2. The trajectories of the 30- and 60-cm movement amplitudes tend to be qualitatively different. Some 30-cm movements exhibit the skewed bell shaped profiles seen from the 15-cm movements but many, like the 60-cm movements, demonstrate other kinds of movement characteristics. In these cases, the hand contacts Target 1 then moves back towards the body and upwards. Then the hand moves forward again (away from the torso) and downwards, often approaching Target 2 with a further movement towards the torso, resulting in a looping trajectory.

A final point to note about these trajectories is the relative spatial inconsistency from trial to trial compared to the previous spatial paths presented for

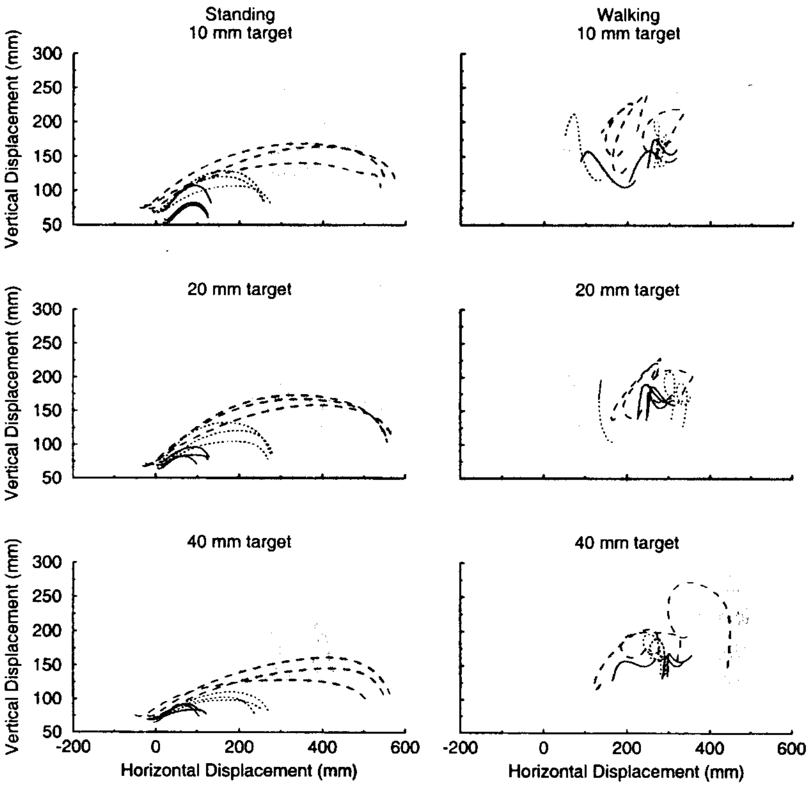



**Figure 2 — Spatial plots involving the forward or horizontal and the vertical displacements of the hand viewed relative to the body as a dynamic frame of reference. The left half of the figure displays the trajectories of the hand for the standing task. The right half shows data for the walking task.**

the end effector compared to a fixed, room-centered frame of reference (Figure 1). Especially in the walking condition the hand's trajectory, relative to the torso, is highly variable from trial to trial. This variability is transformed into consistent trajectories when the whole body's contributions to the movement, as reflected in the movement of the end effector through space relative to a fixed frame of reference, are considered.

*The Movement in the X Dimension.* Since the comparisons of interest were regarding the magnitude of the velocity in the X dimension, the absolute value of PV-X was used so that the data would not be biased by the net displacement of the hand occurring in opposite directions in the standing and walking conditions.

For the measure PV-X, condition interacted with each of amplitude and width. In both cases it is clear from Table 4 that the PV-X was relatively stable in the walking condition compared to the standing condition regardless of changes in amplitude, $F(2, 12) = 134.6$, $p < .0001$, or width, $F(2, 12) = 17.6$, $p <$

**Table 4 Kinematic Characteristics of the End Effector During the Pointing Movement in the X (Antero-Posterior) Dimension Using the Torso as a Moving Frame of Reference**

| Amplitude (cm) | Width (mm) | Peak velocity[a,b] (mm/s) | | Time to peak velocity[c] (ms) | | Time after peak velocity[c] (ms) | | Time after peak velocity[c] (% MT) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stand | Walk | Stand | Walk | Stand | Walk | Stand | Walk |
| 15 | 10 | 708.7 | −935.7 | 172.9 | 76.6 | 169.4 | 284.2 | 47.8 | 78.3 |
| | 20 | 790.5 | −912.3 | 169.6 | 57.4 | 112.0 | 252.0 | 39.7 | 81.1 |
| | 40 | 876.1 | −917.4 | 167.9 | 53.6 | 88.6 | 232.3 | 35.0 | 80.4 |
| 30 | 10 | 1216.0 | −845.0 | 203.4 | 125.0 | 242.8 | 320.0 | 52.9 | 71.8 |
| | 20 | 1287.9 | −885.1 | 203.3 | 71.4 | 186.0 | 333.1 | 47.1 | 82.8 |
| | 40 | 1392.3 | −863.7 | 200.4 | 49.3 | 136.6 | 315.5 | 40.3 | 86.8 |
| 60 | 10 | 1957.4 | −894.9 | 249.2 | 79.3 | 389.7 | 540.1 | 59.2 | 86.3 |
| | 20 | 2024.0 | −907.0 | 246.0 | 56.7 | 302.2 | 505.8 | 43.2 | 89.5 |
| | 40 | 2074.8 | −888.0 | 244.4 | 44.2 | 248.9 | 463.4 | 49.9 | 91.4 |

[a]Significant Condition × Amplitude interaction; [b]Significant Condition × Width interaction; [c]Significant three-way interaction.

.0005. In addition, PV-X was greater in the standing condition (1,370 mm/s) than in the walking condition (894 mm/s), $F(1, 6) = 19.0, p < .005$.

For time to PV-X, the significant three-way interaction of Condition × Amplitude × Width, $F(4, 24) = 3.86, p < .02$, resulted from a consistency across widths for a given amplitude in the standing condition compared to a trend to reach PV-X earlier as width increased for a given amplitude in the walking condition. This was coupled with the time to PV-X occurring sooner in the walking condition.

Time after PV-X yielded a three-way interaction of Condition × Amplitude × Width, $F(4, 24) = 2.38, p < .05$, which reflected an overall greater deceleration time for the walking condition as well as a decreased sensitivity of this measure to changes in width for a given amplitude in the walking condition compared to the standing condition. This was despite the finding that time after PV-X tended to decrease with increased target width and increase with increased amplitude for both the standing and walking conditions. When time after PV-X was normalized to MT, the three-way interaction was again significant, $F(4, 24) = 4.1, p < .02$. There was a tendency for an overall longer proportion of the movement spent decelerating the limb in the walking condition compared to the standing condition. In addition, the percent time after PV-X increased as amplitude increased. Finally, the deceleration time in the standing condition decreased as width increased while the deceleration time increased as width increased in the walking condition. These data are presented in Table 4. (Note that even though the PV-X data is presented as negative values, signifying direction of movement, only the magnitude of the PV-X measures were considered for analyses.)

**Table 5 Kinematic Characteristics of the End Effector During the Pointing Movement in the Z (Vertical) Dimension Using the Torso as a Moving Frame of Reference**

| Amplitude (cm) | Width (mm) | Peak velocity[a] (mm/s) | | Time to peak velocity (ms) | | Time after peak velocity (ms) | | Time after peak velocity (% MT) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stand | Walk | Stand | Walk | Stand | Walk | Stand | Walk |
| 15 | 10 | 465.2 | 477.2 | 98.2 | 100.3 | 244.1 | 260.6 | 69.8 | 71.8 |
| | 20 | 440.3 | 508.2 | 97.3 | 94.0 | 184.4 | 215.4 | 65.0 | 69.2 |
| | 40 | 489.2 | 507.6 | 97.7 | 97.1 | 158.8 | 188.8 | 61.5 | 65.9 |
| 30 | 10 | 575.1 | 552.7 | 107.9 | 105.7 | 338.3 | 339.4 | 74.8 | 75.9 |
| | 20 | 577.0 | 570.7 | 106.4 | 105.5 | 282.9 | 299.0 | 71.9 | 73.9 |
| | 40 | 584.8 | 586.3 | 106.9 | 103.0 | 230.1 | 261.8 | 67.9 | 71.3 |
| 60 | 10 | 782.8 | 615.9 | 122.5 | 118.0 | 516.3 | 501.4 | 80.0 | 80.5 |
| | 20 | 769.9 | 628.6 | 120.7 | 118.8 | 427.4 | 443.6 | 77.3 | 78.6 |
| | 40 | 782.2 | 656.3 | 117.0 | 121.8 | 376.2 | 385.8 | 76.0 | 76.0 |

[a]Significant Condition × Amplitude interaction.

*The Movement in the Z-Dimension.* PV-Z yielded an interaction of Condition x Amplitude, $F(2, 12) = 19.3, p < .0005$. The PV-Z increased as amplitude increased, but did so to a lesser extent in the walking condition than the standing. The temporal measures associated with PV-Z yielded no significant condition-related effects. These data are presented in Table 5.

The kinematic differences between pointing while walking and pointing while standing are clearly more pronounced when the hand movement is considered compared to the body as the frame of reference. In addition, when using the body as the frame of reference the differences between walking and standing are found more in the X dimension of the movement than in the Z dimension. Thus it appears that the displacement in the X dimension caused by locomoting played an important role in the planning and control of the pointing movement.

## *Kinematics: Torso Angles*

In addition to examining the linear movement of the trunk during the pointing movement (which was considered indirectly by removing the trunk's contribution to the movement to observe the arm's contribution to the movement) it was of interest to obtain quantitative information regarding the angular movements of the trunk and their contribution to the pointing movement. Therefore, the angular position of the torso in the transverse plane (i.e., trunk rotation) and the angular position of the torso in the sagittal plane (i.e., flexion/extension at the waist) was determined at the instant of Target 1 contact. In addition, the net change in angle from Target 1 contact to Target 2 contact was calculated. This allowed the determination of body position at the start of the movement and the net change in body position during the movement.

*The Transverse Plane.* At time of Target 1 contact, there were no effects of trunk rotation relating to walking versus standing (e.g., 1.8° clockwise rotation for standing and 4.0° counterclockwise rotation for walking).

Net change in trunk rotation from Target 1 to Target 2, however, yielded two effects involving condition. In the standing condition subjects increased the counterclockwise rotation (i.e., away from the targets) of the torso as the amplitude increased, while there was virtually no change in rotation in the walking condition as amplitude increased, $F(2, 12) = 92.5$, $p < .0001$. Conversely, the amount of rotation in the walking condition was affected by width, with subjects turning toward the targets (clockwise) more as the target diameter decreased, while there was almost no effect of width on the degree of rotation in the standing condition, $F(2, 12) = 26.6$, $p < .0001$. These data are represented in Figure 4.

*The Sagittal Plane.* At the time of contact with Target 1 there was an increase in the degree of flexion, although slightly, at Target 1 in the standing condition as a result of increasing amplitudes, while torso position in the walking condition was unaffected by changes in amplitude, $F(2, 12) = 13.9$, $p < .001$.

Net change in trunk position in the sagittal plane yielded both a condition by amplitude, $F(2, 12) = 55.9$, $p < .0001$, and a condition by width interaction, $F(2, 12) = 9.6$, $p < .005$. In the walking condition, increasing amplitude or width had virtually no effect on the net change in trunk flexion. In the standing condition, however, increases in amplitude greatly increased the net flexion while increases in target width decreased the degree of flexion. These data are presented in Figure 5.

## Discussion

One goal of the present experiment was to explore the performance and control of a traditional experimental task (pointing) under nontraditional constraints. Instead of constraining subjects' body movements to allow controlled investigation of the control of the arm during a pointing task, as is the standard procedure in many studies (e.g., subjects seated, Darling & Miller, 1993; subjects' heads positioned on a chin-rest, Carey, Hargreaves, & Goodale, 1996; subjects' arm supported on a manipulandum, Hay, 1978), subjects were allowed the use of virtually all limb segments, and therefore many degrees of freedom, to successfully complete the task. In addition, the experimental conditions were designed to necessitate the use of the trunk's degrees of freedom in addition to the arm's degrees of freedom to successfully complete a subset of the task conditions.

By adding the factor of task complexity to the above experimental task, the present study also allows us to investigate whether task complexity might be a variable underlying the emergence of motor equivalence. Several of the results presented earlier speak to this issue. First, it is clear from the spatial paths presented in Figures 1A and 1B that subjects were performing the task in distinctly different ways depending on whether or not they were standing or walking. When considering the trajectory of the end effector compared to a fixed, room-centered frame of reference it was difficult to distinguish between pointing movements that were performed while walking from those performed while standing. Examining the movement kinematics of the hand did little to indicate differences between the two conditions. For example, the time to perform the task did not differ between the two versions of the task.

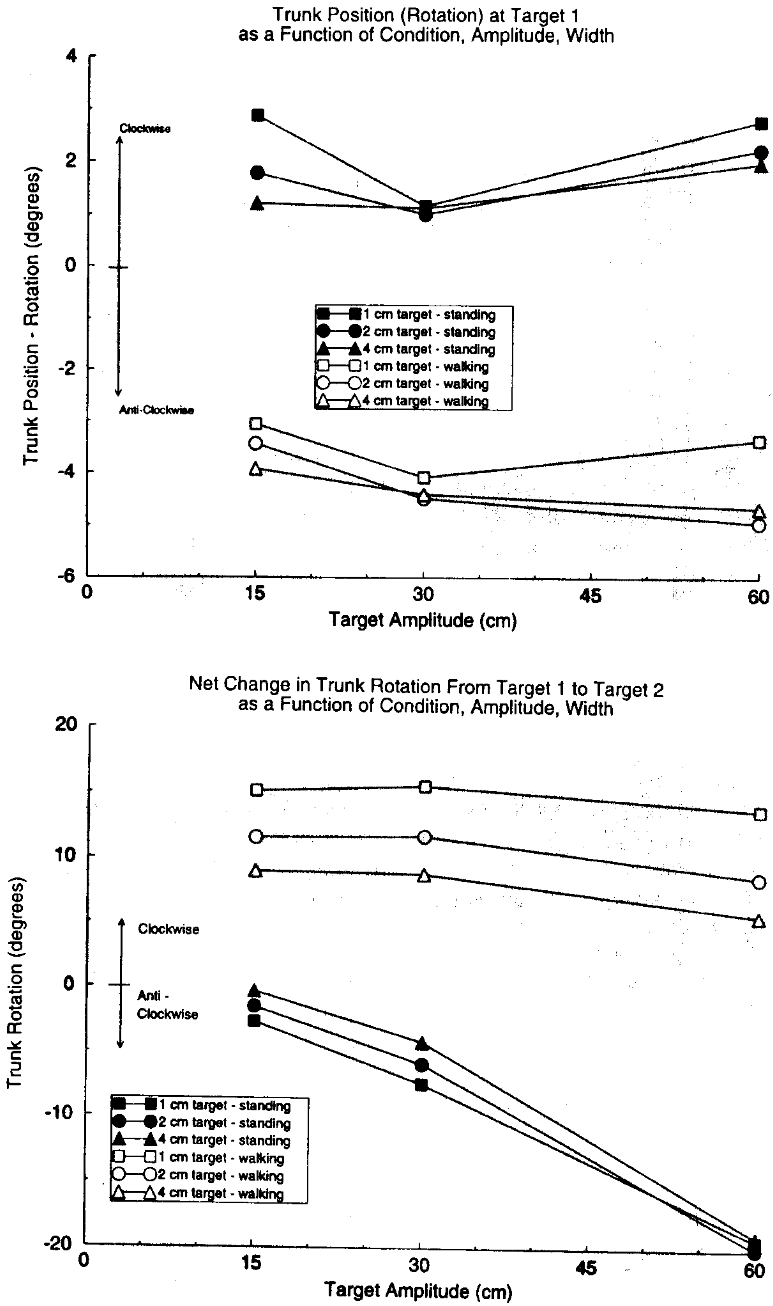



**Figure 4 — These graphs show the angular position of the torso in the transverse plane (i.e., trunk rotation) at the instant of Target 1 contact (Figure A, top) and the net change in angle from Target 1 contact to Target 2 contact (Figure B, bottom).**

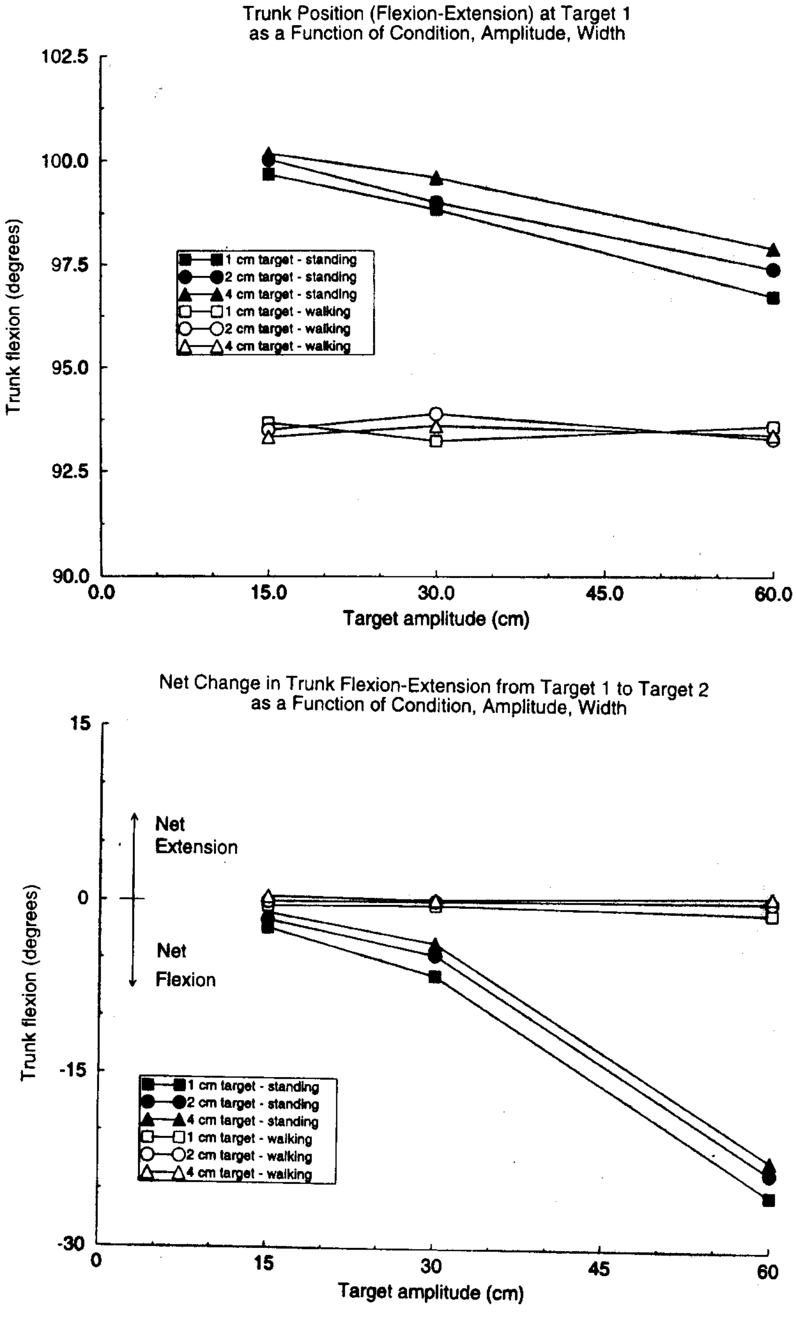



**Figure 5 — These two graphs show the angular position of the torso in the sagital plane (i.e., flexion/extension at the waist) at the instant of Target 1 contact (Figure A, top) and the net change in angle from Target 1 contact to Target 2 contact (Figure B, bottom).**

When the movement of the hand was considered relative to the subject's torso as a moving frame of reference, a dramatically different picture emerged. In the standing condition, the familiar skewed bell-shaped trajectories were seen. In the more difficult walking condition, however, the trajectories were profoundly different, as the net displacement of the hand was backward, toward the torso. In addition, looping spatial trajectories were observed in both the 30 and 60 cm movements, reflecting the hand moving towards the torso and up, then forward slightly, then down and back toward the torso again. As could be expected, these differences in the spatial trajectory of the limb resulted in kinematic differences between the standing and walking tasks. Two- or three-way interactions involving these two tasks were found for all four dependent measures in the forward dimension, while interactions were only found for one measure in the vertical dimension. This is not surprising, considering that the movements of the hand in the walking task reflect a compensation for the torso's forward displacement during locomotion, and the walking subject's torso would contribute much less to the movement in the vertical dimension.

It is interesting to note that although subjects were performing the task differently when walking as opposed to standing, they nonetheless were able to perform the task with an equivalent degree of speed and accuracy. As reported earlier, neither movement time nor standard deviation in the X or Y dimensions were found to be statistically significant. These results clearly indicate that motor equivalence, or a variable means to an invariant end (Abbs & Cole, 1987), allowed the performers to successfully complete a task in the same time but with completely different modes of coordination.

A final place where task complexity appeared to trigger the emergence of motor equivalence is in the analyses of torso angles. It was observed that in order to assist in the successful completion of the task, subjects employed varying degrees of both flexion-extension and rotation movements at the waist. For example, the extent to which flexion at the waist occurred in the standing condition was influenced by target size. More specifically, smaller targets elicited a greater degree of flexion. It is noteworthy that this relationship between trunk kinematics and the accuracy constraint was not observed by Saling et al. (1996) when subjects performed a seated grasping task to two different sized objects placed beyond arm's reach. A possible explanation for these contradictory results is that the paradigm employed by Saling et al. (1996) simply did not offer enough complexity to elicit significant torso contributions. In other words, it is quite reasonable to assume that any compensations required to grasp a dowel 22 mm in diameter versus one that is 67 mm in diameter could be made at the level of the hand and without having to alter the contribution of the torso.

From the above, it would follow that if a similar study was designed such that one of the experimental conditions was considerably more complex than the other, differences in the use of the torso in the execution of the task would become apparent. Steenbergen et al. (1995) conducted just such an experiment. Using a similar trunk-assisted reaching paradigm, subjects were required to reach for and grasp either an empty cup or one filled with coffee. Indeed, it was shown that when subjects were reaching for the filled cup, there was a significantly greater torso contribution than when reaching for an empty cup. These findings, taken together with the results of the present experiment, would seem to suggest that the contribution of complimentary body segments (i.e., the torso) to an on-going movement is a function of task complexity. Furthermore, we predict that if the complexity of a combined upper and lower extremity task were increased even further, not only would greater adjustments be seen in the torso but possibly in the gait as well. This matter is currently under investigation in our laboratory.

In summary, we have presented evidence that task complexity may be one variable leading to the emergence of motor equivalence in a pointing task. First, it was shown that although the underlying coordination of the limb system with the posture system differed considerably, subjects were able to perform the task as quickly and as accurately when walking as when standing. This occurred despite the fact that hand kinematics were vastly different between the two conditions. In addition, it was found that increasing the index of difficulty of a task resulted in greater contributions of the torso to the overall movement. Together, these findings indicate that the human motor system is capable of deriving numerous and equally effective methods to ensure the successful completion of a task. Moreover, we have suggested that motor equivalence presents itself as a control strategy to cope with increasing task demands. The fact that decreasing target width (thereby increasing the index of difficulty) resulted in the successful reorganization of control parameters is a testimony to this belief. Therefore, motor equivalence allowed the participants of this study to successfully complete the task regardless of the additional task demands imposed upon them. In conclusion, it is our contention that the methodology employed herein, as well as others we have cited using similar, complex dual-task paradigms, are the means by which to gain insight into how human motor coordination changes to meet task demands.

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