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Workspace location influences joint coordination during reaching in post-stroke hemiparesis

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Abstract

The purpose of this study was to determine the influence of workspace location on joint coordination in persons with post-stroke hemiparesis when trunk motion was required to complete reaches beyond the arm's functional reach length. Seven subjects with mild right hemiparesis following a stroke and seven age and gender matched control subjects participated. Joint motions and characteristics of hand and trunk movement were measured over multiple repetitions. The variance (across trials) of joint combinations was partitioned into two components at every point in the hand's trajectory using the uncontrolled manifold approach; the first component is a measure of the extent to which equivalent joint combinations are used to control a given hand path, and reflects performance flexibility. The second component of joint variance reflects the use of non-equivalent joint combinations, which lead to hand path error. Compared to the control subjects, persons with hemiparesis demonstrated a significantly greater amount of non-equivalent joint variability related to control of the hand's path and of the hand's position relative to the trunk when reaching toward the hemiparetic side (ipsilaterally), but not when reaching to the less involved side. The relative timing of the hand and trunk was also altered when reaching ipsilaterally. The current findings support the idea that the previously proposed "arm compensatory synergy" may be deficient in subjects with hemiparesis. This deficiency may be due to one or a combination of factors: changes in central commands that are thought to set the gain of the arm compensatory synergy; a limited ability to combine shoulder abduction and elbow extension that limits the expression of an appropriately set arm compensatory synergy; or a reduction of the necessary degrees-of-freedom needed to adequately compensate for poor trunk control when reaching ipsilaterally.

Keywords

Stroke; Reaching; Synergy; Coordination

Introduction

The study of reaching movements both within and beyond the workspace of the arm is critical to determine the extent of reaching deficits in individuals with hemiparesis because these two types of reaches require different amounts of trunk motion. In addition, the trunk is a massive segment that potentially contributes substantial interaction torques to the arm. It has been established that persons with hemiparesis have difficulty coping with interaction torques (Beer et al. 2000). Despite this fact, limited quantitative information is available regarding the influence of trunk control during reaching in persons with hemiparesis (Cirstea and Levin 2000; Levin et al. 2002; Roby-Brami et al. 2003). The available studies reveal that persons with hemiparesis use greater trunk motion and recruit the trunk earlier in the hand's movement

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compared to control subjects reaching to the same distance. When reaching beyond arm's length, the amount of trunk motion used by subjects with hemiparesis is inversely related to their ability to extend the elbow and is associated with a disruption of shoulder-elbow joint coordination (Cirstea and Levin 2000; Michaelsen et al. 2001; Levin et al. 2002; Roby-Brami et al. 2003). Thus, deficits in arm interjoint coordination apparently lead to a change in the trunk recruitment strategy to ensure relatively successful performance (Levin et al. 2002).

Previous studies of reaching movements involving the trunk in healthy persons have proposed the existence an *arm compensatory synergy* that functions to modify the arm joint angles to adjust for the addition of, or changes in, trunk motion without affecting the end effector's trajectory (Ma and Feldman 1995; Archambault et al. 1999; Pigeon et al. 2000). Rossi et al. (2002) showed that this synergy operates primarily up to the time of peak hand velocity, after which time the trunk contributes to the actual hand transport, when reaching beyond arm's length. In contrast, in patients with a stroke, the trunk contributes to the hand's movement from the onset of movement (Levin et al. 2002). This difference in the timing of trunk's contribution to hand movement suggests that the arm compensatory synergy may be altered in persons following a stroke.

In a recent study of pointing to targets within arm's reach, subjects with mild-to-moderate hemiparesis exhibited alterations in the way the joints were combined on average, i.e., in the sharing pattern among the joints, as revealed by principal components analysis (Reisman and Scholz 2003). This latter feature is the more commonly addressed feature of a motor synergy. However, these same patients also exhibited a degree of performance flexibility that was similar to control subjects, as determined by the extent to which equivalent joint motions were used to achieve the same hand path (Reisman and Scholz 2003). This component of joint variance reflecting flexibility in coordinating the joints is considered an important, but often ignored, feature of a movement synergy (Latash et al. 2003). At the same time, a second component of joint variance that reflects non-equivalent joint combinations, leading to greater hand path variability, was significantly higher in the patients. Thus, the observed performance flexibility in the patients came at a cost. The method of the uncontrolled manifold (UCM) approach was used to identify the two components of variance. This method has been used in previous studies of a variety of motor tasks, revealing that performance flexibility is a common feature of the control of a variety of task-related variables (Scholz and Schoner 1999; Scholz et al. 2000, 2002; Domkin et al. 2002; Reisman et al. 2002a, b; Tseng et al. 2002). This method is employed here, in part, to help understand whether the arm compensatory synergy, as defined by Feldman and colleagues (Ma and Feldman 1995; Archambault et al. 1999; Pigeon et al. 2000), is altered in persons with hemiparesis.

The overall purpose of the present study was to investigate whether persons with hemiparesis retain flexibility in coordinating their joints when reaching to obtain targets placed beyond their arm's length. Based on previous findings that persons with mild-moderate hemiparesis exhibit flexible patterns of coordination when reaching within arm's length (Reisman and Scholz 2003), it may be hypothesized that the same would be true when reaching beyond arm's length. However, because the role of the trunk in reaching movements in persons with hemiparesis apparently differs from healthy persons, particularly when reaching beyond arm's length, (Michaelsen et al. 2001; Levin et al. 2002), we hypothesized that the stroke subjects would exhibit less flexible patterns of joint coordination (evidenced by lower amounts of equivalent joint motion and higher non-equivalent joint motion) compared to control subjects when they reached beyond their arm's length. We also hypothesized that this difference would be particularly evident when the patients reached toward their hemiparetic side.

Methods

Participants

Seven participants (ages = 64.4 ± 13.5 years) with right hemiparesis following a first unilateral stroke involving their left hemisphere and seven neurologically healthy individuals (ages = 64.8 ± 11.4 years) participated in this study. Control subjects were age and gender matched to the patients and had no musculoskeletal problems affecting either arm. All subjects were right-hand dominant. All subjects gave approved written consent (Human Subjects Review Committee, University of Delaware), before participating. The subjects with hemiparesis were recruited as a sample of convenience through referrals from local physical therapy clinics and stroke support groups.

Clinical evaluation

Potential patients were screened and excluded if they scored less than 20 on the Mini-Mental State Exam (Folstein et al. 1975), less than 40/56 on the Berg Balance Scale (Shumway-Cook et al. 1997), had greater than eight errors on the Motor Free Visual Perception Test, had a cerebellar lesion based on MRI or CT scan or had other neurologic, musculoskeletal or vascular conditions affecting arm, trunk or pelvic movement. All patients were also administered the arm portion of the modified Fugl-Meyer (Lindmark and Hamrin 1988) and the Fugl-Meyer scales (Fugl-Meyer et al. 1975), and the sensation, proprioception, and pain assessment portions of the Fugl-Meyer (Fugl-Meyer et al. 1975). Scores on the Orpington prognostic scale revealed that all subjects had deficits associated with a minor stroke according to this scale (score of <3.2) (Lai et al. 1998). Demographic and clinical data are summarized in Table 1.

Reaching task

Subjects reached to targets placed at a distance of 160% of their functional arm length (FAL) in both the contralateral (CL) and ipsilateral (IP) workspaces (30° to the left and right of midline). FAL was defined as the distance from the acromion process of the shoulder to the metacarpalphalangeal joint of the index finger when the subject raised his/her arm as close to 90° elevation as possible and extended the hand forward as far as possible without using the trunk.

In the starting position, subjects sat on a modified adjustable bench. Their feet were placed flat with the hips and knees flexed to 90° and $\approx 50\%$ of the thigh's length supported. For all tasks, subjects grasped a wooden dowel of 3.5 cm diameter to which a magnet was attached on the bottom. The handle and arm rested in a small trough that allowed for control of initial arm position. The subject's arm rested at their side in 0° of shoulder flexion and 90° of elbow flexion to control for starting height (Fig. 1). Subject's initial trunk starting position was controlled via a series of rods that lightly touched the subject's upper trunk and pelvis when the correct position was obtained. The target object, a lightweight disk, was placed on a tripod at knee height (Fig. 1).

Subjects' preferred reaching speed was determined by asking them to reach to the CL target at a comfortable speed. Then, to ensure a consistent speed across trials, which was determined in pilot experiments to be otherwise quite difficult for the patients, a metronome was adjusted so that the interval between two pulses matched 160% of the preferred movement time. This percentage was chosen based on pilot testing with non-disabled and hemiparetic subjects as the percentage of preferred speed that subjects in both groups considered as relatively fast, yet could complete. Subjects were instructed to initiate their reach on any metronome beat of their choice, to retrieve the object on the next beat using the magnet attached to the handle, and to return to the starting position by the third consecutive beat. They were not given instructions regarding hand path trajectory. Subjects were given multiple practice trials to familiarize them

with the task. Experimental trials began once the subject was able to complete two consecutive trials correctly matching the metronome. Twenty trials, presented in blocks of five with a random order of target direction for each block, were completed. Subjects were offered rest breaks as needed and no subject complained of fatigue. Only the hemiparetic limb (right limb for control subjects) was tested.

Data collection

A six-camera VICON™ (Oxford Metrics, UK) motion measurement system recorded motion (120 Hz) of seven rigid bodies containing retro-reflective markers, placed on the thigh, pelvis, upper trunk, upper shoulder girdle, arm, forearm and hand. Data from markers placed at each target location were captured and used to create a local coordinate system whose x -axis was aligned with a vector from the starting position to the target and whose y and z axes were orthogonal (following the right-hand rule). Data rotated into this coordinate system was used to calculate movement onset and termination (see Data reduction section) and test hypotheses regarding control of hand path extent (x -axis) and direction (yz -axes).

Data reduction

Three-DOF scapula, shoulder, hip and lumbosacral joint angles, one-DOF elbow and forearm (pronation-supination), and two-DOF wrist angles were calculated (Soderkvist and Wedin 1993) from the filtered (5 Hz, bidirectional second order Butterworth filter) marker coordinate data. See Scholz et al. (2000) for details.

Movement onset (termination) was determined as the time when the velocity of the filtered hand marker exceeded (returned) to 1% of the maximum velocity, using an automatic algorithm verified by visual inspection. Each trial's joint angles were time-normalized to 100% of the movement period (termination-onset) using cubic-spline interpolation (Matlab™).

Conceptual framework: the UCM

Utilizing the UCM method, the degree to which flexible patterns of joint coordination were used to stabilize the path of the hand and the relative position of the hand with respect to the trunk was determined (Scholz and Schoner 1999; Scholz et al. 2000) [See Appendix and Scholz et al. (2000) for mathematical details]. A conceptual description of the method is provided below.

Many different combinations of the redundant joints of the arm and trunk can be used to achieve a particular hand position. Consider, for example, holding your finger on a doorbell while wiggling around the joints of your arm. Given a geometric model that relates the arm's joint angles to the fingertip position, a linear estimate of the sub-space in joint space representing all combinations of those joint angles that yield the fingertip position on the doorbell are obtained as the null space of the Jacobian matrix relating changes in fingertip position to changes in arm joint angles. We have referred to this sub-space as an UCM. A different UCM exists for every possible fingertip position.

From this perspective, a stable hand path during reaching is achieved by the CNS through a sequence of UCMs in joint space, each representing a given hand position along the path. Theoretically, generating an identical hand path across many reaching repetitions, all performed under identical conditions, could be achieved by choosing the same sequence of joint combinations on each repetition (i.e., the same identical joint combination within each UCM defining the sequence of hand positions). Alternatively, different sequences of equivalent joint combinations on each repetition, consistent with the same hand path, could be used, i.e., variations in joint combinations that are constrained to lie within the sequence of UCMs. The former strategy would suggest an attempt to optimize the trajectory of joint angles for a given

hand path by minimizing overall joint variance. The latter strategy suggests that the CNS takes advantage of available motor abundance, leading to the use of flexible patterns of joint coordination to achieve a stable hand path. In this sense, motion within the UCMs is uncontrolled, although, in practice there are likely other constraints that limit the extent to which such variation occurs.

If a stable hand path is important to task success, its control can be considered an inherent *goal* of the CNS. Consequently, all joint angle combinations that achieve a stable hand position at each point along the hand's path can be considered *goal-equivalent* solutions to joint coordination. Variance of joint angle combinations across repetitions of the task that lead to a consistent position of the hand is thus considered goal-equivalent variance (GEV). Variance of joint angle combinations across repetitions that leads to variable hand positions is referred to as non goal-equivalent variance (NGEV). The UCM method partitions overall joint configuration variance into these two components.

Data analysis

Dependent variables

1. Goal-equivalent and non goal-equivalent variance calculated along movement extent with respect to control of two task-related variables: (a) absolute hand path position and (b) the vector length between the sternum and hand (relative hand–trunk position). Each variance measure was normalized to the appropriate DOFs. For example, for control of movement extent (i.e., movement along a straight line to the target), NGEV is the component of joint configuration variance lying orthogonal to the UCM divided by one (i.e., representing a one-dimensional control direction), whereas GEV is the component of joint configuration variance lying within the UCM, divided by 15 (16 joint angles minus 1 DOF of the task variable). The normalized difference (V_D) between GEV and NGEV was also obtained as

$$V_D = \frac{(GEV - NGEV)}{(\text{Total variance} / 16)}.$$

A positive normalized difference indicates that inter-joint error compensation tends to stabilize the particular task variable. The greater the error compensation, the higher will be V_D . A negative value reflects poor control or stabilization of the task variable. For this analysis of the components of joint configuration variance, as well as the variance measures to follow, variance is computed across trials at comparable sample values after the reaches have been normalized to 100% based on their onset and termination. The variance computed at each point in normalized time was then averaged across early, middle and late phases of the reach (see below), and obtained at the time of movement termination, to simplify data presentation and analysis.

1. The actual variance of the hand path extent, computed across trials at each point in normalized time.
2. The variance of the length of the vector or relative position between the hand and trunk, computed across trials at each point in normalized time.
3. The variability of the resultant C7 marker position (trunk variability), computed across trials at each point in normalized time.
4. The relative time of the peak velocity of the A-P trunk movement or of the hand's path along movement extent with respect to movement termination.

Independent variables—The independent variables were: (a) target workspace location (CL or IP), (b) phase (early, middle, late, termination) and (c) group (stroke or control).

Separate mixed design ANOVA's with group as the grouping factor and movement phase, target location and variance component as repeated factors were used to test for differences in joint configuration variance. A group by movement phase by target location ANOVA was used to evaluate task variable variance, trunk variability and the relative timing of peak velocity of the hand and trunk. The Mann–Whitney U test was used when a lack of homogeneity (Levene test) was found for hypothesized comparisons. Statistical tests were performed on variables averaged over three selected phases of the time-normalized forward reaching movement: (1) “Early” 1–40%; (2) “Middle” 40–60%, or around the time of peak velocity; (3) “Late” 70–90% of the movement, and at hand movement termination (“Termination”).

Results

Average reach distance was 0.916 m for the subjects with hemiparesis and 0.949 for the healthy controls. This difference was not significant ($P=0.178$).

Task variable variance

Representative figures of the hand's trajectory when reaching to the IP target are shown for a subject with hemiparesis and the matched control in Fig. 2. Individuals with hemiparesis had greater variance of hand path extent at movement termination than controls when reaching to either target (Mann–Whitney U , $P<0.05$; Table 2). Variance of the relative hand–trunk position was greater in persons with hemiparesis for the last two movement phases only when reaching ipsilaterally (Mann–Whitney U , $P<0.01$).

While not defined as a task variable in this study, we measured variability of the trunk because of its importance to the reaching task. Trunk variability was computed across trials at each point in sampled time and then the average variability across each phase of the movement was calculated. Across movement phase, the variability of the trunk was greater for the subjects with hemiparesis, regardless of target direction ($F_{1,12}=5.39$, $P<0.05$, Fig. 3). There was also a main effect for target with greater trunk variability when reaching ipsilaterally for both groups ($F_{1,12}=7.15$, $P<0.05$, Fig. 3).

Qualitative differences in joint coordination

Figure 4 shows a typical angle–angle plot depicting relative movement of the shoulder and elbow and of the shoulder and trunk (hip angle) when reaching ipsilaterally. Figure 4c, d illustrates that the control subject's reach begins with combined shoulder abduction and hip flexion and, after slight initial elbow flexion, elbow extension. The remainder of the hand's transport is then accomplished by combined elbow extension and hip flexion. In contrast, the individual with hemiparesis (Fig. 4a) shows a similar combination of elbow and shoulder abduction only at the beginning of the movement. While the elbow continues to extend throughout the hand's movement, it is severely limited compared to the control subject, requiring other degrees of freedom (DOF) to compensate. Shoulder abduction is increased somewhat compared to the control subject and continues in combination with hip flexion until the end of the reach (Fig. 4b). This finding is consistent with previous reports of reaching movements involving the trunk in persons with hemiparesis (Levin et al. 2002).

Performance flexibility revealed by joint configuration variance

When comparing groups or conditions, a larger normalized difference (V_D) between GEV and NGEV could result from lower NGEV, higher GEV or a combination of both. Therefore, when differences in this variable are found between groups, the results for GEV and NGEV are also presented.

Movement extent— V_D tended to be smaller and often negative (i.e., $NGEV > GEV$) for patients compared to control subjects in the late movement phase (Mann–Whitney U , $P=0.110$, Table 3) and at movement termination (Mann–Whitney U , $P<0.005$, Table 3), but only when reaching ipsilaterally, with no significant differences present in the earlier movement phases. This group difference was due to larger $NGEV$ in the hemiparetic group (target $\times$ UCM $\times$ group, $F_{1,12}=5.43$, $P<0.05$; Fig. 5), indicating less ability to channel movement variability into goal-equivalent directions.

Relative hand–trunk position— V_D related to control of the relative hand–trunk position differed significantly between the groups or approached significance at all movement phases when reaching ipsilaterally but not contralaterally (Mann–Whitney U , early: $P<0.05$, middle: $P<0.05$, late: $P=0.064$; termination: $P<0.01$). This resulted from hemiparetic individuals having lower GEV (i.e., less flexibility of joint coordination patterns) and higher $NGEV$ (more non-equivalent joint combinations) than controls (target $\times$ UCM $\times$ group, $F_{1,12}=3.03$, $P=0.10$; Fig. 5).

Figure 6 presents individual differences in V_D at movement termination. With only one exception (S2–C2, Fig. 6b), subjects with hemiparesis had a smaller V_D related to control of both movement extent and relative hand–trunk position than their matched control when reaching ipsilaterally. Note that for several persons with hemiparesis, V_D was often negative ($NGEV > GEV$; Fig. 6).

Relative timing of hand and trunk movement

When computed relative to the movement phase of the hand, the hand's peak velocity for control subjects occurred earlier than the peak velocity of the trunk, regardless of the target direction (Mann–Whitney U : $P<0.05$; Fig. 7). For persons with hemiparesis, however, this relationship was true only when reaching to the CL target (Mann–Whitney U : $P<0.05$, Fig. 7). For IP reaching, peak velocity of the hand and trunk occurred nearly simultaneously.

Discussion

Individuals with mild hemiparesis demonstrated a similar amount of both goal-equivalent and non goal-equivalent joint combinations as did control subjects when reaching contralaterally (away from the hemiparetic side) beyond arm's reach. The use of equivalent patterns of joint coordination to control the hand's path or the relative position of two hands reflects an important yet often ignored feature of a motor synergy, namely flexibility of coordination of motor elements to achieve the stability of task variables (Latash et al. 2003). This feature has been reported previously for reaching within arm's length in both healthy adults (Domkin et al. 2002; Tseng et al. 2002) and in individuals with mild to moderate hemiparesis (Reisman and Scholz 2003). A new finding of the present study is that persons with hemiparesis demonstrated both lower values of goal-equivalent joint variance and significantly higher $NGEV$ when reaching with trunk motion toward the hemiparetic side (IP target) than did control subjects. Moreover, the patients exhibited $NGEV$ that was equal to or higher than goal-equivalent joint variance.

Two important questions arise from this new finding. First, why do individuals with mild hemiparesis demonstrate less selective flexibility of joint coordination when reaching beyond arm's length but not when reaching within arm's length (e.g., Reisman and Scholz 2003)? Second, why would such difficulties be selective to reaching in the IP workspace? Perspective on these questions can be gained from previous research that has investigated reaching movements that involve the trunk (Ma and Feldman 1995; Saling et al. 1996; Archambault et al. 1999; Adamovich et al. 2001; Rossi et al. 2002).

Decreased joint coordination flexibility and the arm compensatory synergy

The existence of an *arm compensatory synergy* has been previously investigated using a “trunk arrest” paradigm, where trunk motion is unexpectedly prevented from occurring on random trials during reaching to CL and IP targets (Adamovich et al. 2001; Rossi et al. 2002). Based on the results, the investigators’ concluded that: (1) the trunk contributed to the hand’s movement only after the hand reached its peak velocity, (2) the trunk’s contribution to hand movement is minimized by compensatory arm joint movements until after peak velocity, and (3) the arm compensatory synergy seems to play a greater role when reaching ipsilaterally compared to contralaterally (Adamovich et al. 2001; Rossi et al. 2002).

In the present study, persons with hemiparesis showed higher NGEV relative to GEV for controlling both the hand’s absolute movement path and the relative hand–trunk position when reaching ipsilaterally. Given that it has been hypothesized that the role of the arm compensatory synergy is to adjust arm joint motions to stabilize hand position when trunk motion would alter that position, it is possible that higher non goal-equivalent joint variance indicates an inadequate arm compensatory synergy in these subjects. This hypothesis is supported by the fact that in healthy subjects, the arm compensatory synergy has been shown to be most important when reaching ipsilaterally (Rossi et al. 2002) and the subjects with hemiparesis showed joint coordination flexibility that was less selective only when reaching ipsilaterally. In addition, previous findings suggest that subjects with mild to moderate hemiparesis show similar joint coordination flexibility as healthy controls when the reaching movement does not incorporate trunk motion and thus, an arm compensatory synergy is not required (Reisman and Scholz 2003).

The reported alterations of the relative timing between hand and trunk movement in the patients of this study also support the hypothesis of an altered arm compensatory synergy when subjects with hemiparesis reach ipsilaterally. Previous studies have demonstrated that the time of peak hand velocity precedes the time of peak trunk velocity when the reaching movement incorporates trunk motion (Saling et al. 1996; Wang and Stelmach 1998). In the present study, this was found for reaches to both targets for the healthy control subjects and for CL reaches in the individuals with hemiparesis. In contrast, when the individuals with hemiparesis reached ipsilaterally, the time of hand and trunk peak velocity occurred almost simultaneously. This indicates that from early in the movement, the relationship between the hand and trunk was altered and supports the proposition that the arm compensatory synergy is altered in these subjects.

Potential mechanisms

What are the potential causes of decreased flexibility of joint coordination observed when subjects with hemiparesis reached ipsilaterally beyond arm’s reach? The first possibility is related to the gain of the arm compensatory synergy. It has been suggested that this gain determines the degree to which the arm joints will compensate for trunk movement (Adamovich et al. 2001; Rossi et al. 2002). Given that the gain for the purported arm compensatory synergy is thought to be set via central commands, it is possible that control of these gains are altered due to the brain insult in patients with stroke, leading to the changes observed in arm and trunk joint coordination. Specifically, if the gain is variable from trial to trial, this will lead to variable arm joint compensation and greater non goal-equivalent variability. This would be observed most profoundly when reaching ipsilaterally because the arm compensatory synergy is most important when reaching in this direction (Rossi et al. 2002), consistent with our results.

A second possibility is that the gain of the arm compensatory synergy is appropriately set, but the tight coupling between certain joint motions that is often observed in persons with

hemiparesis may limit the expression of the synergy. Specifically, it has been shown that as the level of isometric shoulder abduction torque generated by the hemiparetic subject is increased, the capacity to generate elbow flexion torque with the paretic limb is enhanced, while maximum elbow extension torques decrease substantially (Beer et al. 1999). Additionally, when subjects with hemiparesis attempt to produce an isolated, isometric shoulder abduction torque, abnormal secondary elbow flexion torques are produced (Dewald and Beer 2001). In a reaching task, when hemiparetic subjects were required to reach to IP or straight-ahead targets while actively abducting the shoulder to maintain the arm level to the ground, elbow extension torques were markedly reduced compared to when active abduction of the shoulder was not required (Beer et al. 2004). Thus, there appears to be a strong coupling between shoulder abduction and elbow flexion in persons with hemiparesis for IP and straight-ahead reaching. The tight coupling between these joint motions will likely limit the flexibility of joint coordination because of the limited ability to vary the relative amount of each joint's contribution to hand movement to compensate for deviations in other joints' motions when reaching ipsilaterally.

Both of these mechanisms could contribute to the higher NGEV, or variance leading to hand path error, found in this study. The fact that the relative timing of trunk and hand motion was found to be altered in the patients when reaching ipsilaterally adds support to the hypothesis of poor control of the central gain of the arm compensatory synergy.

A somewhat different although complementary explanation is suggested by the results of the current experiment, however. The present results suggest that there is a synergy not just of the joints of the arm compensating for trunk motion early in the reach, but that the arm and trunk are united in a functional synergy throughout the reach such that unexpected variations of any one joint may be compensated by changes in other joints. However, this compensation requires the availability of adequate DOF. This is supported by the result that early in the IP reaching movement, the subjects with hemiparesis demonstrated a joint coordination pattern that stabilized the hand's path, although the relationship between the hand and trunk was not stable. This finding would suggest, on the one hand, that the individuals with a stroke have difficulty controlling trunk movement consistently from trial to trial (as supported by the finding of increased trunk variability in the subjects with hemiparesis), leading to an inconsistent trunk–hand relationship. However, if the arm joints compensate adequately for variations in the trunk's movement, the hand's path can be kept relatively stable from trial to trial, as was the case early in the reach. After the first half of the movement, however, both the trunk–hand relationship and the absolute hand path were less stable as evidenced by $GEV \approx NGEV$. Given that patients with hemiparesis are known to have limitations in their ability to combine elbow extension and shoulder abduction (Beer et al. 2004) and have limited elbow extension, particularly later in the movement as the hand moves further from the body, the finding of $GEV \approx NGEV$ likely reflects the fact that the arm now has inadequate DOF to adequately compensate for variations in the trunk's movement. Therefore, both the hand path and trunk–hand relationship were less stable. This argument, if correct, would suggest that improved ability to combine shoulder abduction and elbow extension over a range of movement, as well as improved control of the trunk, is an important consideration when retraining patients to use their hand functionally.

Consistency of hand path and joint coordination variance

Actual hand path variance along movement extent and the variance of the relative hand–trunk position were larger for hemiparetic individuals compared to their matched controls when reaching ipsilaterally during the same movement phases for which the normalized variance difference, V_D , between two components of joint variance was significantly smaller for these subjects. V_D for individuals with hemiparesis was smaller because of higher NGEV (hand

extent) or because of a combination of lower GEV and higher NGEV (relative hand–trunk position), which is important because only NGEV leads to task variable variability. However, this relationship is nonlinear, such that the magnitude of the relationship changes with changes in limb segment geometry along the movement path (Scholz and Schöner 1999). Even when the differences in NGEV between the groups did not reach significance, they were qualitatively similar to differences in task variable variance, supporting the finding of less selective use of flexible joint combinations to control the hand's path (late in movement) and the relative trunk–hand position (throughout movement) when the subjects with hemiparesis reached ipsilaterally.

Conclusions

Persons with mild post-stroke hemiparesis exhibit less selective use of equivalent patterns of joint coordination, or performance flexibility, compared to matched control subjects when reaching *beyond* arm's length toward the hemiparetic side. This contrasts to previous results that revealed similar performance flexibility between persons with mild hemiparesis and control subjects when reaching *within* arm's length (Reisman and Scholz 2003). It is suggested that the results of the present study may be due to changes in the central commands that are thought to set the gain of the arm compensatory synergy, which adjusts arm joint coordination when the trunk is included in the reaching movement. The results may also be due to a limited ability to combine shoulder abduction and elbow extension that limits the expression of an appropriately set arm compensatory synergy or due to a reduction of the necessary degrees-of-freedom needed to adequately compensate for decreased control of the trunk when reaching ipsilaterally.

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Appendix

The initial step in estimating GEV and NGEV is to obtain the geometric model relating the task-related variable, r , (e.g., the position of the hand) to the joint configuration θ . This is done using the product of exponentials formula (Murray et al. 1994). The state-space configuration for the hypothesis about controlling the position of the hand is, in our experiment, composed of 16 angles (three at the scapula, shoulder, hip and lumbosacral joints, two at the elbow—flexion–extension and pronation–supination, two at the wrist—flexion–extension and abduction–adduction).

Small changes in r are related to changes in θ through the Jacobian, which is the matrix of partial derivatives of the task variable, r , with respect to the joint angles, θ . For example, if the task variable under consideration is the position of the hand, the geometric model relating hand position and the joint configuration is

$$\text{Hand}(\mathbf{r}) = \mathbf{R}_{\theta_1} \times \mathbf{R}_{\theta_{i+1}} \times \cdots \times \mathbf{R}_{\theta_n} (\mathbf{d}_i + \mathbf{s}_h) + \mathbf{p}_{\theta_1} + \mathbf{R}_{\theta_1} \times \mathbf{p}_{\theta_{i+1}} + \cdots + \mathbf{R}_{\theta_{n-1}} \times \mathbf{p}_{\theta_n}$$

where, Hand is the three-dimensional position of the hand, $\mathbf{R}_{\theta_i}$ is the rotation matrix associated with rotation about the first axis of the first joint contributing to the position of the hand and $\mathbf{R}_{\theta_n}$ is the rotation matrix associated with rotation about the last axis of last joint contributing to the position of hand.. The variable $\mathbf{d}_i$ is the distance from the origin of the body referenced coordinate system (foot marker) to the joint proximal to the hand (wrist) and $\mathbf{s}_h$ is the length from the wrist to the anterior-most hand marker. $\mathbf{p}_{\theta_i}$ is the translation vector associated with rotation about the first axis of the first joint contributing to the position of hand (that is, the first joint proximal to the base frame), $\mathbf{p}_{\theta_n}$ is the translation vector associated with rotation about the last axis of the last joint contributing to the to the position of the hand.

The second step is to estimate the linear approximation to the UCM from the geometric model. Because the UCM differs for each value of the task variable, a decision is necessary as to what value to use for the estimation. In reality, both joint configurations and task variables vary from trial to trial. Based on the assumption that the normalization of movement time has aligned matching states of the underlying joint space across trials, we compute the mean joint configuration, $\bar{\theta}$ at each percent of the movement. Effectively, the value of the task variable, $\bar{r}$, associated with that mean joint configuration is represented by the UCM. Again, continuing with the example for the hand position, the linear approximation to the UCM was obtained from the geometrical model, linearized around the mean joint configuration:

$$\mathbf{r} = \mathbf{J}(\bar{\theta}) \times (\theta - \bar{\theta}).$$

Here, $\mathbf{J}$ is the Jacobian, composed of $\partial r / \partial \theta_i$, where $i = \{\text{hip, LSJ, scapular, shoulder, elbow and wrist joint angles}\}$, obtained at each point in sampled time. The linear approximation of the UCM is then the null-space of the Jacobian (the linear subspace of all deviations from the mean joint configuration that are mapped onto zero by the Jacobian). Using Matlab™ for the numerical computation of the null-space, the actual value of the joint configuration minus the mean joint configuration at each point along the movement path of each trial is decomposed into a component that lies within this null space and a component in its complement. The components of the deviation vector of the joint configuration lying within the UCM and those in its complement are then squared, summed across dimensions of the UCM (i.e., sum of squares), and averaged across all trials, resulting in variance measures. The estimates of variance were then divided by the appropriate number of DOF. For example, for the hypothesis

about controlling the hand position, the joint configuration space is 16-dimensional and the task variable is three-dimensional. Therefore, the null space has 13 dimensions. Thus, variance of the joint configuration within the UCM is divided by 13. The variance perpendicular to the UCM (i.e., variance that changes the value of the task variable from its mean value) is divided by three. This normalized variance is reported as variance per DOF within the UCM (or GEV) and orthogonal to the UCM (NGEV).

Fig. 1. Experimental set-up. *A, B* Instrumentation used to standardize trunk starting position. *C* Arm trough used to standardize arm starting position

Fig. 2. Trajectory of the hand in the medial/lateral-anterior/posterior direction for a subject with hemiparesis (**a**) and the matched control (**b**) when reaching to the ipsilateral target. *Each line represents an individual trial. Arrows indicate the direction of movement*

Fig. 3.

Average (across subjects) trunk variability (contralateral target, control: *hatched bars*; ipsilateral target, control: *stippled bars*; contralateral target, stroke: *gray bars*; ipsilateral target, stroke: *black bars*). Error bars represent $\pm$ SEM. Results are shown for the early, middle, late and terminal phases of the reaching movement. Trunk variability is greater for the subjects with hemiparesis than for healthy, control subjects

Fig. 4.

Angle-angle plots of shoulder abduction-hip flexion (**a, c**) and shoulder abduction-elbow extension (**b, d**) for a subject with hemiparesis (**a, b**) and a matched control subject (**c, d**) reaching ipsilaterally. *Each line* represents an individual trial. The *arrow* indicates the direction of movement. The starting position of the hip angle (thigh and pelvis perpendicular) and full elbow extension is indicated as 0° on the y-axis, full shoulder abduction is indicated as 0° on the x-axis

Fig. 5.

Average (across subjects) goal-equivalent variance (GEV; stroke: *open bars*; control: *hatched bars*) and non goal-equivalent variance (NGEV; adjacent *solid bars*) $\pm$ SEM for the control of **a** hand movement extent and **b** relative hand–trunk position when reaching ipsilaterally. Results are shown for the early, middle, late and terminal phases of the reaching movement

Fig. 6.

Individual differences in the normalized variance difference (i.e., $GEV - NGEV / \text{Total variance per DOF}$) for control of **a** hand path extent and **b** relative hand-trunk position. *Hatched bars*: contralateral target; *Open bars*: ipsilateral target. Each pair of subjects is identified by group (S stroke, C control) and a number

Fig. 7.

Relative time of the velocity peak of trunk and hand movement relative to hand movement termination when reaching contralaterally and ipsilaterally. Data for the subjects with hemiparesis are represented in the *left plot* and data for the age-matched control subjects are represented in the *right plot*. The larger the negative value, the earlier the trunk or hand peak velocity with respect to hand termination. *Error bars* represent ± 1 SEM. Hand peak velocity always occurs earlier than trunk peak velocity, except when the subjects with hemiparesis reach ipsilaterally

Table 1

Characteristics of subjects with hemiparesis

Subject	Lesion location	UE portion: Modified F-M and F-M	Orpington Score	Time since stroke (months)
S1	Ischemic infarct of left thalamus	53/57; 62/66	2.0	26
S2	Ischemic infarct, left pontine lesion with small regions of periventricular ischemia	53/57; 63/66	2.4	6
S3	Ischemic infarct of left putamen extending superiorly into periventricular white matter	50/57; 56/66	2.4	11
S4	Ischemic infarct confined to left insular, subinsular regions	51/57; 62/66	2.8	8
S5	Ischemic infarct, left internal capsule, extending into periventricular white matter	51/57; 58/66	2.0	7
S6	Small hemorrhagic lesion of left pons	51/57; 57/66	2.4	37
S7	Ischemic infarct, left anterior pons	48/57; 58/66	2.4	29

Table 2Variance of performance variables (mm²)

	Extent	Trunk–hand
Contralateral target		
Stroke, early	0.489±0.253	0.532±0.272
Control, early	0.274±0.185	0.238±0.106
Stroke, middle	1.31±0.285	1.56±0.367
Control, middle	0.967±0.318	1.14±0.162
Stroke, late	0.242±0.091	0.9991±0.378
Control, late	0.1791±0.067	0.5267±0.199
Stroke, term.	0.1251±0.047 *	0.4867±0.184
Control, term.	0.0460±0.017	0.2539±0.096
Ipsilateral target		
Stroke, early	0.136±0.029	0.279±0.087
Control, early	0.186±0.056	0.118±0.031
Stroke, middle	0.486±0.175	0.309±0.141
Control, middle	0.652±0.153	0.202±0.023
Stroke, late	0.1515±0.057	0.5676±0.215 **
Control, late	0.1412±0.053	0.3744±0.141
Stroke, term.	0.1423±0.053 *	0.4504±0.170 **
Control, term	0.0677±0.025	0.2321±0.087

*
P<0.05;**
P<0.01

Table 3
Normalized difference between GEV and NGEV (V_D) $\pm$ SEM

	Movement extent	Relative trunk–hand position
Contralateral target		
Stroke, early	0.2991 $\pm$ 0.152	0.5414 $\pm$ 0.104
Control, early	0.1423 $\pm$ 0.150	0.6331 $\pm$ 0.144
Stroke, middle	0.4095 $\pm$ 0.110	−0.1869 $\pm$ 0.236
Control, middle	0.0759 $\pm$ 0.189	−0.0156 $\pm$ 0.263
Stroke, late	0.3975 $\pm$ 0.126	0.3113 $\pm$ 0.162
Control, late	0.6085 $\pm$ 0.062	0.5415 $\pm$ 0.192
Stroke, term.	0.4061 $\pm$ 0.134	0.4290 $\pm$ 0.201
Control, term.	0.4628 $\pm$ 0.029	0.5789 $\pm$ 0.126
Ipsilateral target		
Stroke, early	0.2713 $\pm$ 0.112	−0.1354 $\pm$ 0.175**
Control, early	0.3481 $\pm$ 0.139	0.4767 $\pm$ 0.139
Stroke, middle	0.3230 $\pm$ 0.176	−0.0798 $\pm$ 0.067**
Control, middle	0.2693 $\pm$ 0.131	0.2328 $\pm$ 0.147**
Stroke, late	−0.0078 $\pm$ 0.199*	0.1728 $\pm$ 0.107**
Control, late	0.4782 $\pm$ 0.130	0.6656 $\pm$ 0.090
Stroke, term.	−0.2751 $\pm$ 0.188***	0.0820 $\pm$ 0.126***
Control, term.	0.6138 $\pm$ 0.070	0.7153 $\pm$ 0.078

*
 $P < 0.10$;

**
 $P < 0.05$;

 $P < 0.01$