# Trunk Compensation during Bimanual Reaching at Different Heights by Healthy and Hemiparetic Adults

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# Abstract

The authors explored how trunk compensation and hand symmetry in stroke survivors and healthy controls were affected by the distance and height of virtual targets during a bimanual reaching task. Participants were asked to reach to four different virtual targets set at: 90% of their arm length at shoulder, xiphoid process, and knee height, and 50% of their arm length at xiphoid process height. For the stroke group, for all targets, the hands' movements were more asymmetrical than those of the healthy group, with more asymmetry observed in the direction of gravity, and trunk forward displacement values were larger and more variable. The knee targets had the largest trunk displacement values; index of curvature and trunk displacement were strongly correlated with participants' impairment scores. A strong correlation was found between the hands' asymmetry in the anterior/posterior direction for the shoulder targets, and the impairment scores. The results suggest that target height influences the degree of trunk compensation and hand symmetry during bimanual reaching by hemiparetic participants.

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People with hemiparesis tend to compensate for lost function by taking advantage of the redundant degrees of freedom of their bodies. For example, they may use a shoulder hike to compensate for lack of elbow flexion when lifting their arms, or use the unaffected hand to complete tasks that would normally involve the affected side. By using these compensatory movement strategies, individuals manage to maintain the ability to interact with the surrounding environment. However, in general, compensatory movements should be minimized when possible as they can be considered maladaptive [1], [2].

A common compensatory movement when reaching [3] and orienting the hands for grasping [4] is anterior trunk displacement. Although a healthy unimanual forward-reaching movement does involve trunk displacement, the magnitude of displacement is more than 4.5 times greater in stroke survivors [5]. Moreover, hemiparetic stroke survivors tend to use trunk displacement even when the target is well within arm’s reach [6]. Evidence suggests that training the arm movements of stroke survivors while limiting the amount of trunk displacement can lead to improvements in arm reaching kinematics, i.e., increased elbow extension and shoulder flexion [7].

In the stroke literature, most of the attention on compensatory movements has been given to the study of unimanual reaching and its connection to trunk compensation [3]–[5], [8]. However, older adults tend to use both hands at the same time for most of their daily activities [9]. Furthermore, evidence suggests that practicing bimanual movements leads to the coupling of homologous muscles in both limbs, which promotes the activation of both cerebral hemispheres [10]. Moreover, in healthy individuals, bimanual training can lead to improvements in unimanual performance [11]. Therefore, including therapy exercises that involve bimanual co-ordination is crucial if we want stroke survivors to regain their lost bimanual abilities.

During activities of daily living, people are required to reach in a three-dimensional space, and are not constrained to the transverse plane. However, when trunk compensation has been investigated using unimanual tasks, little attention has been given to the effect of target height on trunk compensation and reaching performance. This study aims to complement the current unimanual and limited bimanual [12] compensatory literature, by analyzing anterior trunk displacement, completion time, symmetry and straightness of the hands' movements during a bimanual reaching task. Targets at different elevations were included to investigate the effects of target height on the reaching performance of both healthy and hemiparetic participants.

## Method

### Participants

Ten hemiparetic stroke survivors (Table 1) were recruited through local community centres, private rehabilitation clinics, stroke recovery groups, and the research group's website. The inclusion criteria admitted adults with hemiplegia as a result of a non-traumatic stroke at least six months prior to the study. Participants were also required to have the ability to maintain a sitting position in a chair without arm rests and to move their affected arm from their knee to their chest and back without any assistance from their strong side. Participants were excluded if they had upper-limb surgery in the past 6 months, shoulder subluxation or significant shoulder or trunk pain, uncorrected visual impairments, or any other orthopaedic or neurological conditions that could affect their arm or trunk.

**Table 1. Demographic and clinical data for stroke participants**

| | Sex | Age | Height (cm) | DHBS | HS | Lesion Site | Type of Stroke | Time since stroke (months) | FMA | MAS Biceps | MAS Triceps | MAS Wrist Flex. | MAS Wrist Ext. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S-01** | M | 66 | 180.0 | R | L | R DB of PCA, IC/T | H | 34 | 62 | 0 | 0 | 1 | 1 |
| **S-02** | M | 56 | 177.8 | R | L | R BG | H | 20 | 25 | 2 | 2 | 2 | 3 |
| **S-03** | M | 75 | 177.8 | R | R | L P | I | 20 | 60 | 0 | 0 | 0 | 0 |
| **S-04** | M | 67 | 167.6 | R | L | R CN, PL of R IC, L EC | I | 37 | 39 | 1 | 2 | 2 | 0 |
| **S-05** | M | 58 | 177.8 | L | L | R F | H | 72 | 46 | 2 | 2 | 2 | 2 |
| **S-06** | M | 51 | 170.2 | R | R | L CR | I | 15 | 51 | 1 | 0 | 0 | 1 |
| **S-07** | M | 59 | 177.8 | R | L | R SF | I | 12 | 60 | 0 | 0 | 0 | 0 |
| **S-08** | F | 75 | 152.4 | R | L | R LN, EC | H | 8 | 66 | 0 | 0 | 0 | 0 |
| **S-09** | M | 74 | 185.4 | R | R | L MCA | I | 24 | 58 | 0 | 0 | 0 | 0 |
| **S-10** | F | 73 | 162.6 | R | L | R MCA | I | 96 | 45 | 1+ | 1 | 0 | 1+ |
| **Average** | | **65.4** | **172.9** | | | | | **33.8** | | | | | |
| **SD** | | **8.9** | **9.8** | | | | | **28.5** | | | | | |

BG=Basal Ganglia, CN=Caudate Nucleus, CR= Corona Radiata, DB=Deep Branch, DHBS=Dominant hand before stroke, EC=External Capsule
F= Frontal, FMA=Fugl-Meyer, HS=Hemiparetic side, H=Hemorrhagic, IC=Internal Capsule, I=Ischemic, L=Left, LN= Lentiform Nucleus
MCA= Middle Cerebral Artery, MAS=Modified Ashworth, P=Pontine, PCA= Posterior Cerebral Artery, PL= Posterior Limb, R=Right
SF=Sylvian Fissure, T=Thalamus

The control group included seven females and three males, with a mean age of 65.2 ± 8.68 years, and a mean height of 165.8 ± 9.7 cm. All the participants in this group were right hand dominant. The inclusion criteria were over age 45, with no previous stroke or significant brain injury, and the ability to maintain a sitting position in a standard chair.

All participants provided written informed consent. The study was approved by the Clinical Research Ethics Board of the University of British Columbia.

## Clinical Assessment

Prior to the reaching protocol, stroke participants were administered the Modified Ashworth Scale (MAS) to measure abnormal muscle tone through resistance to passive movements [13] as a means of describing the sample. This assessment was selected because muscle overactivity can interfere with movement and cause abnormal posturing [14] that may influence participants' performance on the reaching tasks involved in the study. This clinical information about the sample can help readers to determine the generalizability of the findings. Standardized administration methods as described in Bohannon & Smith (1987) were used to assess the biceps, triceps and wrist flexors and extensors. The upper extremity subsection of the Fugl-Meyer Assessment (FMA) was also administered as a descriptive measure of performance-based upper extremity impairment severity using standardized procedures described by [15]. Greater severity of motor impairment as indicated by lower FMA scores has been correlated with decreased functional ability in daily activities (Sullivan et al., 2011). An occupational therapist with several years of experience in neurorehabilitation performed both clinical assessments. Results are presented in Table 1.

## Experimental Setup

The experimental system (Figure 1) consisted of two haptic robotic devices (Geomagic® Phantom® Premium™ 1.5), a motion tracking camera (Microsoft Kinect™ v1), and a computer running Windows® 7.

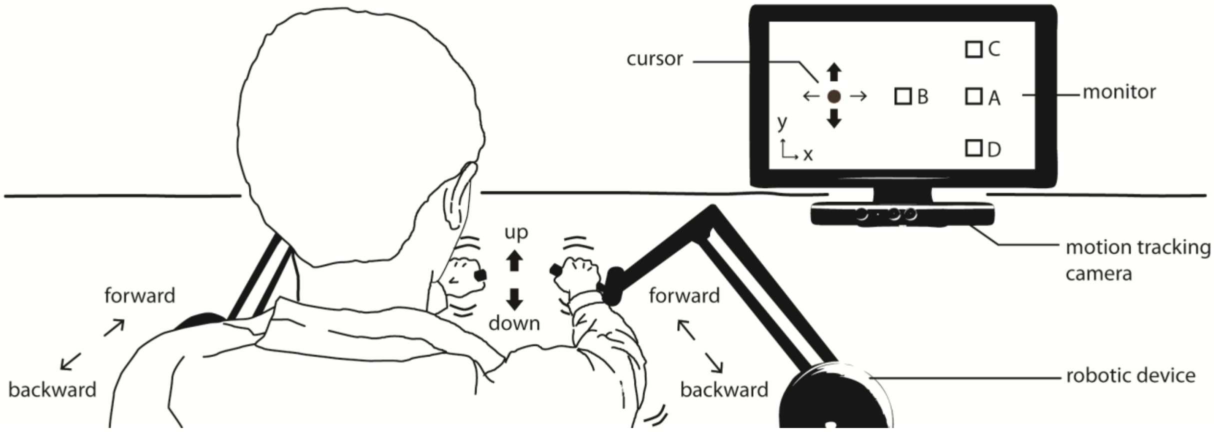

**Figure 1.** Experimental Setup. Up/Down and Forward/Backward movements of the hands were mapped to up/down (y-axis) and left/right (x-axis) cursor movements, respectively. Left/Right movements of the hands were not mapped. On each trial, only one target was presented to the participant. Target A = 90% fully extended arm at xiphoid height, Target B = 50% fully extended arm at xiphoid height, Target C = 90% fully extended arm at shoulder height, Target D = 90% fully extended arm at knee height

The Kinect camera measured trunk anterior displacement in the sagittal plane, which was defined as the displacement of the tracked skeleton's sternal joint in the Z direction. This camera has the potential to be used in at-home rehabilitation programs because of its low cost and commercial availability. The resolution[1] (X and Y: 3.4mm and Z: 12mm) and displacement accuracy in the depth direction (~25 mm (Mobini, Behzadipour, & Saadat Foumani, 2013; Webster & Celik, 2014)) were deemed sufficient to measure the relative trunk displacement of stroke survivors and healthy participants, based on the magnitude of compensation measured in previous unimanual studies (Cirstea & Levin, 2000; Michaelsen et al., 2004; Michaelsen & Levin, 2004).

Participants performed bimanual reaching exercises towards a virtual target by grasping and moving the stylus ends of the two Phantom robots. The devices measured the position of the

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[1] PrimeSense$^{TM}$. Available from: http://www.i3du.gr/pdf/primesense.pdf

hands of the participants via the built-in encoders (resolution[2]: 0.03 mm). All motors were turned off, and no forces were produced by the robots.

A monitor was placed in front of the participants to display a targeting game that required them to reach forward to play (Figure 2). In addition, the experimenter used another monitor to control the system and display the tracking stability of the Kinect's skeleton and the position of the robots. Only the research team was able to see this monitor during the study. The system was controlled via a custom program built in LabVIEW (National Instruments™), which was able to acquire joint data from the motion tracking camera and the Cartesian position of the robots' end-effectors. The custom program employed libraries from the Kinesthesia and the Phantom Omni Toolkits (Mechanical Engineering, University of Leeds).

**Figure 2.** Side view of reaching movement and setup

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[2] 3DSYSTEMS. Available from: http://www.geomagic.com/files/4714/4241/0953/Phantom_Premium_EN_Web.pdf

## Reaching Task

Participants sat in a stationary chair. The backrest was adjusted to keep the trunk of the participant at 90° to the thighs, and to support at least 75% of the thighs in the chair’s seat. A custom height-adjustable footrest ensured that all participants had their knees flexed at 90° when seated. The robotic devices were placed on top of a stand on each side of the participant, at a distance that ensured that the workspaces of the robots were large enough to accommodate movements to all targets. For the system, the positive X axis was to the right of the participant, the positive Y axis was pointing up, and the positive Z axis was in the forward direction (towards the camera).

At the beginning of the experiment, the system was calibrated by asking participants to place their hands in front of their xiphoid process and to use their thumbs to locate this bony structure. This position would become the starting position for all targets. Users were then asked to fully extend their unaffected arm from the starting position to the following elevations: shoulder height (i.e., arm parallel to the ground), chest height (arm extended at xiphoid height), and knee height (arm extended downwards without touching their ipsilateral knee).

The calibrated distances were used by the system to place the virtual targets (Figure 1) at the following horizontal locations: Target A (90% fully extended arm at xiphoid height), Target B (50% fully extended arm at xiphoid height), Target C (90% fully extended arm at shoulder height), Target D (90% fully extended arm at knee height). The vertical locations of the targets were placed at 90% of each calibrated height. The vertical and horizontal locations were chosen to ensure that participants were able to reach to the targets with their unaffected arm without using any trunk compensation, and to prevent the robotic devices from reaching a singularity.

Given that the targets were displayed in a 2D environment, only the Z (forwards/backwards) and Y (up/down) movements of the hands were mapped to the virtual cursor.

After the calibration was completed, our custom bimanual Visual Symmetry (VS) algorithm [19] mapped the movement of the hands to the virtual cursor. This algorithm supported the use of bimanual symmetric movements, in which both hands needed to move the robots' end-effectors at the same time, and in the same direction. In contrast, if only one hand moved or both hands moved in opposite directions there would not be any progression towards the virtual target.

On every iteration of the program (~30Hz), the VS algorithm compared the displacement vectors of both hands to assess which one had the smallest magnitude, and the smallest vector was mapped to the cursor's movement. This approach was used to promote the use of more controlled and symmetrical movements, as large unimanual motions were prevented from changing the position of the cursor. Figure 3 shows the algorithm for mapping the hands' Z movement to the X component of the virtual cursor, where $x_c$ is the X component of the virtual cursor's vector, $K_x$ is the control-display gain for X, $z_L$ is the Z position of the left hand, $z_R$ is the Z position of the right hand, $\boldsymbol{L}$ and $\boldsymbol{R}$ are the left and right hand's displacement vectors, and $k$ is the program iteration number. The control-display gain was defined as the constant multiplier that mapped the movement of the pointing devices to the movement of the virtual cursor. This constant was set based on the subject's arm length and on the screen resolution. Figure 3 only shows the mapping for the cursor movement in the X direction; however, this algorithm was also applied to the Y direction using the hands' up/down movement.

$$x_{C,k} = \begin{cases} 0 & if\ k = 0 \\ x_{C,k-1} + K_x(\Delta z_L) & if\ \{[(\Delta z_L > 0) \wedge (\Delta z_R > 0)]\ \vee\ [(\Delta z_L < 0) \wedge (\Delta z_R < 0)]\}\ \wedge\ \{\ \|\boldsymbol{L}_k\| < \|\boldsymbol{R}_k\|\}^{a} \\ x_{C,k-1} + K_x(\Delta z_R) & if\ \{[(\Delta z_L > 0) \wedge (\Delta z_R > 0)]\ \vee\ [(\Delta z_L < 0) \wedge (\Delta z_R < 0)]\}\ \wedge\ \{\ \|\boldsymbol{L}_k\| > \|\boldsymbol{R}_k\|\}^{b} \\ x_{C,k-1} & otherwise \\ & k = 0,1,2,3\ \ldots \end{cases}$$

**Figure 3.** Visual Symmetry Mode Algorithm. $x_c$: X component for virtual cursor vector, $K_x$: control-display gain for X, $z_L$: Z position for left hand, $z_R$ :Z position for right hand, $L$ and $R$ are the displacement vectors for the left and right hands, $k$: iteration number

[a] *If both hands are moving together in the positive or negative direction, and the left hand moved less, then the movement of the left hand is mapped to the virtual cursor*

[b] *If both hands are moving together in the positive or negative direction, and the right hand moved less, then the movement of the right hand is mapped to the virtual cursor*

The main objective for the participants was to reach towards a virtual target (one per trial), and to retain the virtual cursor inside the target's bounds for one second. Participants were asked to perform each reach at a comfortable speed, similar to that which they would use during everyday tasks to reach for a physical object. To enable participants to become familiar with the system, they performed five practice trials for each target location, which were presented in a random order, in blocks of four targets. If at any point during the practice run there was a need for system recalibration, the system was reinitialized, and the subject completed 5 trials with the new calibration. After completing each target, participants returned their hands to the initial position before moving on to the next target. To ensure that participants were returning to the correct starting position, verbal and visual guidance to stay within 25 mm of their initial calibrated position was provided. This condition promoted measurement repeatability of upper body movements when reaching to the different targets.

After the practice trials, participants reached towards each target fifteen times, and their trajectories were recorded for data analysis. Targets were presented in a random order in blocks of four, and after completing each target participants were required to return to the initial position. The returning movements towards the initial position were not recorded because during this time participants were free to move without complying with the VS condition.

## Data Analysis

Data from the Kinect motion tracking camera and the robots' end effectors were obtained at ~30 Hz. The Kinect joint data, filtered by the Holt Double Exponential Smoothing Method provided by the Microsoft Developer SDK v1.8, reduced jitteriness and stabilized joint positions from the skeletal tracking algorithm.

Anterior trunk displacement provided a measure of trunk compensation employed by participants. This movement was defined as the displacement of the sternal joint of the Kinect skeleton in the Z direction. If at any point during the study the skeleton was observed to inaccurately represent the participant's body (a research assistant monitored the skeleton tracking during all trials), the trial was discarded and repeated at the end of the nominal 15 trials in each block.

To assess the symmetry between the hands, the Root Mean Square (RMS) Error in the Y and Z direction was calculated. The X direction was not calculated, as movements in this direction were not mapped to cursor movement. The error was estimated by taking the difference between the positions of the hands. This calculation was repeated for every data point, and the RMS value for the differences was calculated to obtain the final results.

The index of curvature provided a measure of the straightness of the path of the hands towards the target. This variable was defined as the ratio of the actual 3D hand path to the length of a straight line measured from the starting point to the target. With this measurement, a value of 1 would represent the hands following a perfectly straight path towards the target.

Completion time was measured from the moment the participant was presented with the target until the target was reached and disappeared.

## Statistical Analysis

Normality was evaluated using box and normal Q-Q plots, as well as the Shapiro-Wilk test. The assumption of equal variances was tested using Levene's Test for Equality of Variance. When the assumption of equal variances was not met, Welch's test was employed instead of the standard t-test. Cohen's $d$ was employed as a measure of effect size, with small ($d$ = 0.2), medium ($d$ = 0.5) and large ($d$ = 0.8) effects [20]. Similar to the between-groups comparisons, the effects of the within-groups results were calculated using the standard deviations of each compared group [21].

For repeated measures ANOVA (RMANOVA), the assumption of sphericity was tested using Mauchly's Test. Based on the value of epsilon [22], the Greenhouse-Geisser ($\varepsilon$<0.75) or the Huynh-Feldt ($\varepsilon$ > 0.75) corrections were employed.

For pairwise comparisons, when the assumption of normality was met, the paired t-test was employed. In addition to the $p$ value, the mean of the differences ($\bar{x}_{diff}$) and its standard error ($SE_{diff}$) are indicated.

For all post-hoc tests, the $p$ values were adjusted using the Bonferroni-Holm correction for multiple comparisons [23].

When the assumption of normality was not met, non-parametric tests were employed for the between- (Mann-Whitney U test) and within- (Friedman and Sign tests) group comparisons. As a result of the non-symmetrical distributions of the differences in the within-group comparison, we were not able to use the Wilcoxon Signed Rank test. Instead, we had to rely on the less powerful Sign test.

Given that the general form of the Mann-Whitney test evaluates stochastic dominance [24], and not location shift, the Probability of Superiority (*PS*) was employed to measure effect size [25]. Since $PS = 0.5$ means equal chance (no effect), as values depart from 0.5, the size of the effect increases. When the Sign test was employed, the Probability of Superiority for dependent groups ($PS_{dep}$) was used to measure effect size [25]. A $PS_{dep}$ equal to 1 indicates that all values in one level were larger than in the other. In addition to the $p$ value of the Sign test, the median ($m_{diff}$) and the interquartile range ($IQR_{diff}$) of the differences are indicated in the results.

To measure variability of the data, the coefficient of variation (*CV*) was calculated.

Correlations between the ordinal FMA scores and the ratio variables were analyzed using the Spearman's correlation coefficient ($r_s$), with very weak (<0.2), weak (0.2-0.39), moderate (0.40-0.59), strong (0.60-0.79), and very strong (0.8-1.0) associations [26].

All statistical tests were conducted in SPSS Statistics v22.0 (IBM Corp., Armonk, NY). For calculating the effect size of parametric tests, Dr. Lee A. Becker's (University of Colorado) effect size calculator was used.

# Results

## Between-Groups Comparisons

All participants were able to reach to all targets except for S-10, who only reached Target C nine times instead of the required 15, and S-04 who was not able to reach Target C. For both subjects this result was related to difficulty reaching up against gravity because of low motor function. Results from this section are presented in Table 2.

### Table 2. Between-groups comparisons

| | Target A | | Target B | | Target C | | Target D | |
|---|---|---|---|---|---|---|---|---|
| | **Control** | **Stroke** | **Control** | **Stroke** | **Control** | **Stroke** | **Control** | **Stroke** |
| Trunk Displ. (% of target dist.) | 11.4 (11.6) | **34.9 (29.3)***<br>*t(11.76)=2.36*<br>*p=0.036*<br>*d=1.05* | 8.0 (10.1) | 31.6 (32.2) | 10.7 (10.8) | **28.0 (20.8)***<br>*t(11.74)=2.24*<br>*p=0.046*<br>*d=1.04* | 17.3 (14.9) | **48.0 (35.3)***<br>*t(12.11)=2.53*<br>*p=0.026*<br>*d=1.13* |
| Trunk Displ. (mm) | 29.8 (30.8) | **100.9 (81.3)***<br>*t(11.53)=2.59*<br>*p=0.024*<br>*d=1.16* | 11.0 (14.4) | **49.6 (49.5)***<br>*t(10.52)=2.37*<br>*p=0.038*<br>*d=1.06* | 30.0 (30.2) | **92.3 (70.8)***<br>*t(10.58)=2.45*<br>*p=0.033*<br>*d=1.14* | 32.4 (28.2) | **110.4 (85.2)***<br>*t(10.95)=2.75*<br>*p=0.019*<br>*d=1.23* |
| RMS Error Y (mm) | 15.5 [11.4,43.6] | **52.8 (25.6)****<br>*U=16.0*<br>*p=0.009*<br>*PS=0.84* | 13.5 [12.0,33.5] | **38.3 (17.9)***<br>*U=18.0*<br>*p=0.015*<br>*PS=0.82* | 19.3 [14.1,33.8] | **49.5 (21.8)***<br>*U=17.00*<br>*p=0.022*<br>*PS=0.83* | 13.6 [10.7,24.0] | **41.7 (14.9)****<br>*U=15.0*<br>*p=0.007*<br>*PS=0.85* |
| RMS Error Z (mm) | 22.0 (7.3) | **35.4 (15.5)***<br>*t(18.0)=2.47*<br>*p=0.024*<br>*d=1.11* | 19.2 (6.9) | **27.2 (9.3)***<br>*t(18.0)=2.18*<br>*p=0.043*<br>*d=0.977* | 21.5 (7.4) | **33.6 (12.7)***<br>*t(17.0)=2.57*<br>*p=0.020*<br>*d=1.16* | 22.4 (9.4) | **38.4 (15.5)***<br>*t(18.0)=2.78*<br>*p=0.012*<br>*d=1.25* |
| Index Curv. Left XYZ | 1.3 (0.12) | 1.4 [1.2,2.0] | 1.6 (0.31) | 1.6 [1.5,3.3] | 1.5 (0.24) | 1.5 [1.3,3.0] | 1.5 (0.26) | 1.6 [1.4,2.3] |
| Index Curv. Right XYZ | 1.3 (0.10) | 1.4 [1.2,2.1] | 1.5 (0.33) | 1.7 [1.4,3.4] | 1.4 (0.23) | 1.8 [1.4,3.1] | 1.5 (0.24) | 1.6 [1.4,2.8] |
| Time (s) | 5.2 (1.3) | 5.7 [3.6,9.5] | 4.6 (1.4) | 4.8 [3.6,11.0] | 6.9 (2.2) | 6.8 [4.1,16.7] | 5.9 (1.1) | 5.8 [4.4,11.3] |

Mean (SD). Median [1st and 3rd Quartiles]. Significant results are bolded (* P<0.05, **P<0.01 ).

*t(degrees of freedom)=t value. p=p value. d=Cohen's d. U=Mann-Whitney U value. PS=Probability of Superiority. RMS=Root Mean Square*

### 1) *Trunk Displacement*

For all targets, trunk forward displacement values for the hemiparetic group were larger and more variable than for the control group. For the trunk displacement normalized to target distance (Table 2), all differences were statistically significant, except for Target B, which was borderline significant (*t*(10.75) = 2.20, *p* = .05). On average, values for Target A (34.9 ± 29.3%) were approximately three times larger for the stroke group, and two times larger for Target C (28.0 ± 20.8%) and Target D (48.0 ± 35.3%). Similar to the trunk displacement results (not normalized), all differences had a large effect.

The stroke group (Table 2) exhibited larger values of anterior trunk displacement to all targets. On average, values for Target A (100.9 ± 81.3 mm), C (92.3 ± 70.8 mm) and D (110.4 ± 85.2 mm) were approximately three times larger for the stroke group, and four times larger for Target B (49.6 ± 49.5 mm). All differences had a large effect size.

### 2) *RMS Error*

The movements of the hands were more asymmetrical to all targets in the stroke group, with more asymmetry in the direction of gravity. The values for the RMS error in Y and Z, for all targets (Table 2), were significantly higher in the stroke group. The median values of the Y errors of the stroke group, for all targets, were close to three times the values in the control group. In addition, the average values for the Z errors of all targets were approximately 1.5 larger in the stroke group. The findings suggest that for all targets, the group’s movements tended to be more asymmetrical regardless of the elevation or anterior distance to the targets. In addition, the values for the superior/inferior direction were larger than those for anterior/posterior, providing evidence of more asymmetrical bimanual movements in the direction of gravity.

### 3) *Index of Curvature*

The differences between the indexes of curvature (Table 2) for both the left and right hands were found to be statistically non-significant for all targets (all values $p > 0.063$). The index of curvature of the stroke group had large coefficients of variation, which could have played a part in reducing the chances of finding significant differences between groups. In the unimanual reaching literature (Cirstea & Levin, 2000; Michaelsen et al., 2001), the index of curvature for stroke survivors tends to be larger than for healthy controls, and results tend to be statistically significant, which provides evidence toward a true difference between groups. Further studies with a larger number of participants could confirm similar results for bimanual reaching.

### 4) *Time*

The differences in reaching times between the control and experimental groups (Table 2) did not reach statistical significance (Target A, $U = 40.0$, $p = .481$; Target B, $U = 38.0$, $p = .393$; Target C, $U = 42.0$, $p = .842$; Target D, $U = 48.0$, $p = .912$). Similar to the index of curvature, the lack of statistical significance in the differences between groups on the time variable was probably a result of the high variability and small sample size of the stroke group (Target A, $CV = 0.72$; Target B, $CV = 0.58$; Target C, $CV = 0.96$; Target D, $CV = 0.89$). The higher-functioning participants in the stroke group exhibited similar completion times as those in the control group, but for subjects with FMA < 50, in most cases, the mean value and variability of their data tended to be higher than those of the control group.

## Within-Groups Comparisons

S-04 was excluded (listwise deletion) from the stroke group calculations only for the within-groups comparisons. This exclusion was made because of the participant's inability to reach the target at shoulder level (Target C) because of limited motor function, which resulted in an incomplete set of data for the omnibus tests (Friedman Test and RMANOVA). All values for the Control group were unchanged (Table 2) for the within-group comparisons. The significant results from the pairwise comparisons are presented in Table 3.

**Table 3. Within-groups comparisons**

| | **Stroke** | | | **Control** | | |
|---|---|---|---|---|---|---|
| Trunk Displacement (% target distance) | **TD>TA***<br>*p=0.024*<br>$m_{diff}=10.53$<br>$IQR_{diff}=14.39$<br>$PS_{dep}=1.00$ | **TD>TB***<br>*p=0.020*<br>$m_{diff}=15.66$<br>$IQR_{diff}=22.10$<br>$PS_{dep}=1.00$ | **TD>TC***<br>*p=0.016*<br>$m_{diff}=7.89$<br>$IQR_{diff}=23.54$<br>$PS_{dep}=1.00$ | **TD>TB***<br>*p=0.012*<br>$m_{diff}=6.62$<br>$IQR_{diff}=4.29$<br>$PS_{dep}=1.00$ | | |
| Trunk Displacement (mm) | **TA>TB***<br>*p=0.024*<br>$\bar{x}_{diff}=44.72$<br>$SE_{diff}=11.11$<br>*d=0.789* | **TC>TB***<br>*p=0.032*<br>$\bar{x}_{diff}=51.89$<br>$SE_{diff}=14.66$<br>*d=0.889* | **TD>TB***<br>*p=0.020*<br>$\bar{x}_{diff}=55.70$<br>$SE_{diff}=13.79$<br>*d=0.898* | **TA>TB***<br>*p=0.036*<br>$\bar{x}_{diff}=18.83$<br>$SE_{diff}=5.74$<br>*d=0.782* | **TC>TB***<br>*p=0.035*<br>$\bar{x}_{diff}=19.03$<br>$SE_{diff}=5.47$<br>*d=0.803* | **TD>TB***<br>*p=0.018*<br>$\bar{x}_{diff}=21.44$<br>$SE_{diff}=5.22$<br>*d=0.956* |
| RMS Error Y (mm) | **TA>TB***<br>*p=0.012*<br>$\bar{x}_{diff}=11.49$<br>$SE_{diff}=2.57$<br>*d=0.613* | | | | | |
| RMS Error Z (mm) | | | | | | |
| Index Curvature Left XYZ | **TC>TA***<br>*p=0.024*<br>$m_{diff}=0.180$<br>$IQR_{diff}=0.578$<br>$PS_{dep}=1.00$ | | | | | |
| Index Curvature Right XYZ | **TC>TA***<br>*p=0.024*<br>$m_{diff}=0.164$<br>$IQR_{diff}=0.680$<br>$PS_{dep}=1.00$ | | | | | |
| Time (s) | **TC>TA***<br>*p=0.023*<br>$m_{diff}=1.33$<br>$IQR_{diff}=9.12$<br>$PS_{dep}=1.00$ | | | **TC>TA***<br>*p=0.020*<br>$\bar{x}_{diff}=1.68$<br>$SE_{diff}=0.436$<br>*d=0.941* | **TD>TB***<br>*p=0.012*<br>$\bar{x}_{diff}=1.29$<br>$SE_{diff}=0.306$<br>*d=1.03* | |

Significant results are bolded (* $P<0.05$, ** $P<0.01$ ). *p= p value.* $m_{diff}$*=Median of the differences.* $IQR_{diff}$*=Interquartile range of the differences.* $PS_{dep}$*=Probability of Superiority for dependent groups.* $\bar{x}_{diff}$*=mean of the differences.* $SE_{diff}$*=Standard error of the differences.* *d=Cohen's d. RMS= Root Mean Square. TA=Target A. TB=Target B. TC=Target C. TD=Target D.*

### 1) ***Stroke Group***

The target at knee height yielded greater trunk compensation in the stroke group, when compared to targets at other elevations. When trunk displacement was normalized to target distance, the values for Target D were consistently larger than those of A, B and C. Trunk displacement was larger for Targets A, C and D when compared to B.

The RMS error in Y was larger for Target A when compared to Target B. The RMS error in Z did not reach statistical significance in the RMANOVA ($p = .053$).

The index of curvature for both hands when reaching to Target C was larger than for Target A.

For stroke participants, the time to get to Target C was significantly longer than for Target A.

### 2) ***Control Group***

After normalizing the trunk displacement with the distance to the target, the values for target D were larger than those for Target B. Trunk displacement for Target B was less than for all the other targets.

The RMS error in Y did not reach statistical significance using the Friedman test ($p = .288$). A similar result was obtained when using RMANOVA for the error in Z ($p = .670$).

The index of curvature for the left and right hands did not reach statistical significance when the targets were compared using RMANOVA (Left, $p = .097$), and the Friedman test (Right, $p = .070$).

For both groups, the time to get to Target C was significantly longer than for Target A. In addition, for the stroke group, the time to get to target D was longer than for target B.

## Correlations with FMA Upper Extremity Motor Scores

Results for this section are presented in Table 4.

**Table 4. Correlations with FMA upper extremity motor scores**

| | Target A | Target B | Target C | Target D |
|---|---|---|---|---|
| Trunk Displ. (% target dist.) | $r_s=-0.511$<br>$p=0.132$ | $r_s=-0.474$<br>$p=0.166$ | $r_s=-0.460$<br>$p=0.213$ | $r_s=-0.614$<br>$p=0.059$ |
| Trunk Displ. | $r_s=-0.584$<br>$p=0.077$ | $r_s=-0.474$<br>$p=0.166$ | $r_s=-0.460$<br>$p=0.213$ | **$r_s=-0.644$**<br>**$p=0.044$*** |
| RMS Error Y | $r_s=-0.225$<br>$p=0.532$ | $r_s=-0.091$<br>$p=0.802$ | $r_s=-0.167$<br>$p=0.667$ | $r_s=-0.024$<br>$p=0.947$ |
| RMS Error Z | $r_s=-0.365$<br>$p=0.3$ | $r_s=-0.103$<br>$p=0.776$ | **$r_s=-0.828$**<br>**$p=0.006$**** | $r_s=-0.584$<br>$p=0.077$ |
| Index Curv. Left XYZ | $r_s=-0.596$<br>$p=0.069$ | $r_s=-0.389$<br>$p=0.266$ | $r_s=-0.494$<br>$p=0.177$ | **$r_s=-0.736$**<br>**$p=0.015$*** |
| Index Curv. Right XYZ | **$r_s=-0.663$**<br>**$p=0.037$*** | $r_s=-0.322$<br>$p=0.364$ | $r_s=-0.510$<br>$p=0.16$ | **$r_s=-0.723$**<br>**$p=0.018$*** |
| Time[a] | $r_s=-0.374$<br>$p=0.287$ | $r_s=0.087$<br>$p=0.811$ | $r_s=-0.311$<br>$p=0.416$ | $r_s=-0.212$<br>$p=0.557$ |

Significant results are bolded (* P<0.05, **P<0.01 ).

*$r_s$=Spearman's correlation coefficient. p=p value.*

[a]Correlation with the "Coordination and Speed" subscale of FMA.

Trunk displacement normalized to target distance exhibited a non-significant moderate (except for target D which was strong and close to *p* = .05) correlation to all targets.

Trunk displacement for Target D exhibited a strong statistically significant correlation with the FMA total upper extremity motor score. All the other targets exhibited a non-significant moderate correlation.

The correlations between the RMS errors in Y and the clinical scores were non-significant, weak (Target A) and very weak (Target B, C and D), with all *p* values above 0.53. For the target at shoulder level, a very strong correlation between the asymmetry of the hands in the anterior/posterior direction and the participants' clinical scores was identified. For the other targets the correlations were non-significant, and very weak (Target B), weak (Target A) and strong (Target D). The correlation between the asymmetry of the hands in the superior/inferior direction toward all different targets was found to be weakly associated with FMA scores. In contrast, the very strong and highly significant correlation between the target at the highest elevation (Target C) and the asymmetry in anterior/posterior could suggest that as the participants move up against gravity, the motions of their hands become more asymmetrical in the transverse plane, and that there may be a direct relationship with decreasing clinical scores. Moreover, two of the participants with lower functional scores (S-04 and S-10) were unable to reach to the highest target the same number of times as the other participants (S-04: 9/15 reaches, S-10: 0/15 reaches), which provides more evidence for this hypothesis. However, the participant with the lowest score (S-02) was able to complete all trials, which calls for a larger sample of participants to be able to generalize these results, and perhaps further exploration of individual variation and kinematic variables that may help to monitor reaching impairment in the direction of gravity.

The index of curvature of both hands to the target at knee height was strongly correlated with the clinical scores. For all other targets the correlation was non-significant, moderate and weak. For the right hand the correlation for Target A and D was strong and significant. For targets B and C the correlations were non-significant, weak and moderate, respectively.

The reach time was not significantly correlated with either the FMA total upper extremity score or the coordination and speed subscale. The non-significant and weak correlation between the reach time and FMA score could be explained by the lack of a time limit or pressure to hit the target. In the present study, it was more desirable to have participants reach as naturally as possible (at their own pace), in order to allow us to measure trunk compensation values that were closer to those presumably used during everyday reaching tasks.

# Discussion

## Trunk Compensation

In stroke survivors, anterior trunk displacement during forward reaching is a common compensatory movement that is typically paired with decreased contribution at the elbow (Cirstea & Levin, 2000; Roby-Brami et al., 2003). Muscle synergies are commonly used to account for a reduction in the resulting degrees of freedom of the upper limb during functional reaching tasks [27]. One of the primary goals of post-stroke rehabilitation is to promote the re-learning of pre-injury motor patterns as a means of improving function [28]. A focus on the recovery of healthy-state motor patterns over the use of compensatory strategies may help to limit loss of range of motion, pain and learned non-use over the long term, as well as to optimize the potential for ongoing improvements into the chronic stage of stroke by means of neuroplasticity (Levin et al., 2009).

In most previous studies, participants have only been asked to perform reaching movements unimanually and to a single height (Michaelsen & Levin, 2004; Levin et al., 2002; Michaelsen et al., 2001). In this study, we investigated if participants would exhibit similar levels of trunk compensation when asked to reach bimanually at different heights and distances. This information is important because many functional tasks involve bimanual reaching at a range of heights, and a more thorough understanding of the degree to which the addition of the less affected arm to the reaching task may affect trunk displacement has implications for the way therapy is structured.

Values for trunk displacement during reaching to targets at shoulder, knee and chest height were larger in the stroke group, when compared to the control group. These results are consistent with what has been documented previously for targets at chest height for bimanual [12] and unimanual reaching [3]. Trunk compensation as a percentage of the target distance for Target B (target at 50% of arm reach) was found to be borderline significant ($p = .05$) when comparing the stroke and control samples. In previous unimanual studies (Levin et al., 2002; Michaelsen et al., 2001), the trunk compensation of stroke survivors when reaching to near targets tended to be higher when compared to the results of the control group. Consequently, we attribute this borderline result to the low number of subjects and their high variances. In addition, the within-group significant results for both the stroke and control groups support the idea that the trunk displacement required to reach Target B was less than for all the other targets.

When comparing the trunk compensation normalized to target distance, the stroke group (within-group comparisons) exhibited consistently larger values when reaching to the target below the chest (Target D) than for all the other distances and elevations, which supports the idea of a relationship between moving in the direction of gravity and the amount of trunk compensation used by stroke survivors. We hypothesize that the reason for larger trunk flexion for targets below the xiphoid process height is that for stroke participants to reach down to a target, they can successfully complete the movement by employing only trunk flexion, with minimal shoulder and elbow movement. On the other hand, if the target is placed above sternal height, utilizing only trunk flexion will move the participant's hand downwards, requiring greater abduction at the shoulder to move the hand upwards, which is a movement that may be more challenging for hemiparetic participants in the presence of flexor synergies [29]. As a result, it would appear that stroke survivors select the movement that requires the least shoulder abduction to reach targets in front of them. Trunk flexion for unimanual reaching towards targets below chest height appears to show a similar trend for healthy older and young adults reaching to physical targets placed in front of them [30]. During data analysis, before we applied the multiple comparisons corrections to the *p* values of the control group, the results for Target D were observed to be the same as those of the stroke group (*p* = .021), which is consistent with the aforementioned study.

Trunk displacement to Target D exhibited a strong correlation with the FMA upper extremity motor scores. This result suggests that stroke survivors with lower FMA scores tend to exhibit more compensatory anterior trunk displacement, especially when they reach towards targets below chest height. The non-significant correlations between the clinical scores and the trunk displacements to the targets at chest level (Targets A and B) differ from previous findings for unimanual reaching (Cirstea & Levin, 2000; Levin et al., 2002; Michaelsen et al., 2001; Michaelsen et al., 2004). This difference could be the result of the low power of the study afforded by the small sample size. However, the strength of the associations were moderate, and the fact that results for Target D were significant even with the small sample suggests that a clear correlation exists between the clinical scores and the trunk compensation used for targets that require the participants to move in the direction of gravity, a reaching height which has not being thoroughly studied in the stroke literature.

For both the left and right hand, the correlation between the index of curvature of Target D and the FMA scores was strong and significant. This finding provides evidence to support the idea that for targets below xiphoid process height, participants tend to move both hands in a less straight trajectory when their motor function is more impaired. Because the main driver for their progression towards the target was trunk flexion, small movements about the hip joint could have resulted in larger displacements of the hands as compared to reaching with a static trunk, resulting in more uncontrolled movements.

## Bimanual Performance

Chronic stroke survivors tend to use their unaffected side 3-6 times more than their affected side for daily activities, and when they do perform bimanual activities, their affected limb is used with less intensity than the unaffected limb (Michielsen, Selles, Stam, Ribbers, & Bussmann, 2012; Wolf et al., 2014). In contrast, healthy individuals perform bimanual tasks with greater frequency than unimanual tasks during daily activities [9]. Post-stroke, increased bilateral upper limb use is also associated with improved task performance in instrumental activities of daily living [33]. Consequently, rehabilitation approaches that promote the use of the affected limb in both unimanual and bimanual exercises may be particularly effective at increasing the overall use of the affected arm, while enabling stroke survivors to practice movements that are closer to those typically employed in everyday tasks. Moreover, in their review of the literature on bimanual movements, Cauraugh and Summers (2005) suggest that bimanual training after a stroke could facilitate neural plasticity as a result of the recruitment of ipsilateral pathways, motor cortex disinhibition, and increased use of corticopropriospinal pathways. As such, clinicians can exploit the neural benefits of practicing bimanual movements through the design of such rehabilitation interventions for stroke survivors. Indeed, bilateral training has been found to be as efficacious as unimanual approaches at improving function of the paretic arm (Wolf et al., 2014).

In this study, we employed a bimanual system to investigate the trunk compensation of stroke survivors and healthy controls. As a measure of bimanual performance we employed the RMS error between the hands' movements. Based on the results for the hands' asymmetry, we hypothesize that the reduction in the active upper limb ROM at higher reaching elevations is a result of the difficulty to lift the paretic arm using shoulder abduction and flexion, while accompanied by elbow extension. This reduction in the ROM during movements that require larger shoulder abduction torques appears to be connected to upper limb flexor synergy [35]. In addition, in the within-group comparisons, the stroke group took more time to reach to the target at the highest elevation (Target C) than to the target at chest level (Target A), which again provides support to the idea that the higher the stroke participants tried to reach, the more difficult the task became. For the control group a similar result was observed when comparing those targets, which suggests that for both populations, the larger torques required to sustain the arm at higher elevations directly impacts the difficulty of the task. Furthermore, the index of curvature of the stroke group was larger for Target C than for Target A, which again supports the idea that stroke survivors may experience increasing difficulty during reaching tasks at higher elevations. Conversely, the control group did not exhibit any effect of gravity on the index of curvature to the different targets.

This information confirms clinical observations that inform the grading of the degree of reaching task challenge based on target height. More importantly, however, is the implication that kinematic information about the symmetry of the hands' movements could provide clinicians with an objective measurement of bimanual performance over the course of rehabilitation for hemiparesis, with lower means and variability implying more symmetrical bimanual movements. This analysis could provide a means of monitoring upper limb improvement over time (Glegg, Hung, Valdés, Kim, & Van der Loos, in press). However, further longitudinal research over the course of the rehabilitation process would be warranted to confirm this method.

## Clinical Implications

The results from this study provide supporting evidence for the hypothesis that hemiparetic stroke survivors employ different magnitudes of trunk compensation when asked to reach to different heights. This information is relevant for clinicians promoting premorbid movement patterns during the rehabilitation of the upper extremities post-stroke. One of the main goals of physical rehabilitation programs is to maximize functional independence through retraining of daily skills [37]; this study supports the concept of performing movements in all directions as being an important consideration in optimizing the patient's recovery, as stroke survivors employ different motions strategies to reach at different elevations. As newer technologies for rehabilitation become available e.g., robotic, virtual, and gaming rehabilitation (Norouzi-Gheidari, Archambault, & Fung, 2012; Lohse, Hilderman, Cheung, Tatla, & Van der Loos, 2014), the approach of performing movements in 3D space should be paramount in the design of these applications.

Previous studies (Woodbury et al., 2009; Michaelsen & Levin, 2004) have provided promising results about how limiting trunk motion can lead to improvements in arm movement quality. These studies have employed physical trunk restraints to limit the trunk movement of stroke survivors [7]. An alternative approach could be to employ augmented feedback (audio, visual) to provide information to hemiparetic patients about their trunk compensation in real-time (Thielman, 2010; Alankus & Kelleher, 2012). Consequently, the results from this study could provide guidance on the different levels of compensation that participants may exhibit when asked to reach at different distances and heights.

The novel integrated system that was presented in this work has the capability of measuring different kinematic aspects of the movements of the hands, arms and trunk. The analysis of these types of kinematic data has the potential to generate indicators of improvement during rehabilitation, which could complement the information obtained by current clinical scales of impairment and function, to further customize and evaluate the outcomes of therapist-prescribed treatment programs.

## Study Limitations

A limitation of this study was the Kinect's accuracy and resolution (Experimental Setup section), which does not allow for the sub-millimeter accuracy of other more expensive and complex systems (e.g., Vicon). However, in this study, the Kinect was able to capture the relative displacements of the trunk for both healthy and stroke survivors, and showed clear differences between populations and targets. The release of Kinect v2, which has a higher resolution and improved skeletal tracking, has the potential to offer an enhanced tracking option for future rehabilitation/motion capture projects.

A second limitation was the mapping of the hand's movements from a forward/backward end effector motion, to a left/right cursor movement on the screen. To mitigate the effects of this mapping on the participants' "normal" motion strategies, we provided them with a set of 20 reaches as part of the familiarization stage. During the practice trials participants could spend as much time as needed to complete the targets, giving them enough opportunity to explore how their hand movements mapped to the virtual cursor.

Finally, a larger sample size should be employed in future studies to further examine the ideas presented in this work.

# Conclusion

Activities of daily living require stroke survivors to reach in a three-dimensional space with variable joint positions/orientations. As a result, employing virtual/robotic rehabilitation systems that promote the use of movements that would be required for users to interact with the real world is crucial. Robotic/virtual systems should not focus on training users in one plane of motion, but instead should promote the use of reaching motions within the entire arm's workspace. In the stroke reaching literature, trunk displacement is identified as a major component of the reaching movements of stroke survivors; however, how this movement is affected by different height requirements had not been yet thoroughly examined, especially for bimanual interventions.

The results obtained in this work provide evidence that stroke survivors exhibit different degrees of trunk compensation and hand asymmetry during reaching to different elevations. We believe that this information is particularly important for virtual/robotic rehabilitation programs that aim to reduce trunk compensation and to promote premorbid movement patterns.

Future work for this project will involve the use of force cues provided by the robotic devices to promote a reduction of trunk compensation, which could have the potential to complement/substitute current therapy approaches that employ physical restraints to limit users' trunk movement.

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