Reducing Trunk Compensation in Stroke Survivors:

A Randomized Crossover Trial Comparing Visual vs. Force Feedback Modalities

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This is an Accepted Manuscript of an article published by ELSEVIER. The Version of Record of this manuscript has been published and is available in Archives of Physical Medicine and Rehabilitation (May 17th, 2017). Available online:

https://doi.org/10.1016/j.apmr.2017.03.034

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Acknowledgments: The authors would like to thank the participants, as well as colleagues Ashea Neil, Keith Lohse, Navid Shirzad, Tina Hung, Stephanie Glegg, Jonathan Marr, Laura Jaquez, Derek Schaper, and Renee Bernard for their assistance.

Financial Support: This work was supported by the Peter Wall Solutions Initiative (11-079), Vancouver, Canada, CONACYT (Consejo Nacional de Ciencia y Tecnología) Mexico (311462), and Canada Foundation for Innovation.

Conflict of Interest: The authors declare that they have no conflict of interest.

Clinical Trial Registration: ClinicalTrials.gov**,** NCT02654951, https://clinicaltrials.gov/ct2/show/study/NCT02654951

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Objective: To investigate whether the compensatory trunk movements of stroke survivors observed during reaching tasks can be decreased by force and visual feedback, and examine whether one of these feedback modalities is more efficacious than the other in reducing this compensatory tendency.

Design: Randomized Crossover Trial

Setting: University research laboratory

Participants: 15 community dwelling older adults: 5 female, 64 ± 11 years old, with hemiplegia from non-traumatic hemorrhagic or ischemic stroke (> 3 months post-stroke), recruited from stroke recovery groups, the research group's website and the community.

Intervention: In a single session, participants received augmented feedback about their trunk compensation during a bimanual reaching task. Visual feedback (60 trials) was delivered through a computer monitor, and force feedback (60 trials) through two robotic devices.

Main Outcome Measures: Primary: Change in anterior trunk displacement measured by motion tracking camera. Secondary: trunk rotation; Index of curvature (measure of straightness of hands' path toward target); RMS error of hands' movement (differences between hands position on every iteration of the program); Completion time for each trial; Post-test questionnaire to evaluate users' experience and system's usability.

Results: Both Visual (-45.6% (45.8) change from baseline, *p=0.004)* and Force (-41.1% (46.1), *p=0.004)* feedback were effective in reducing trunk compensation. Scores on secondary outcome measures did not improve with either feedback modality. Neither feedback condition was superior.

Conclusions: Visual and force feedback show promise as two modalities that could be used to decrease trunk compensation in stroke survivors during reaching tasks. It remains to be established which one of these two feedback modalities is more efficacious than the other as a cue to reduce compensatory trunk movement.

Keywords: rehabilitation, robotics, upper extremity, stroke, therapy.

Abbreviations: Analysis of Covariance (ANCOVA), Fugl-Meyer Assessment (FMA), Reaching Performance Scale (RPS), Root Mean Square (RMS), Upper Extremity (UE).

Stroke survivors with limited upper extremity (UE) motor function due to hemiparesis use their trunk to compensate when reaching forward[1,2,3]. Relying on these compensatory movements to reach can be detrimental to UE recovery[4]. Moreover, reducing the magnitude of trunk compensation by restraining the trunk can lead to improvements in UE movement quality[5,6,7].

Use of trunk restraint physically restrains the person to a chair using straps or a custom harness[8]. An alternative methodology to reduce trunk movements is employing technology to provide augmented feedback about the magnitude of compensation[9,10]. These augmented feedback strategies offer advantages when compared with trunk restraint: the person makes a conscious choice not to compensate, rather than relying on physical restraints that continuously limit body movement, it is less intrusive as there is no need to restrain the person to a chair, it can be employed at home without direct supervision, the feedback intensity can be modified in real time from a remote location, and the active error thresholds and challenge of the task can be automatically adapted as the individual improves. To adopt augmented feedback in common rehabilitation practice, there must be sufficient evidence supporting the efficacy of these alternate feedback methods. In this study, we employed two augmented feedback modalities (visual and force) to provide information to participants about their trunk compensation. The objectives of this study were to investigate: (1) Whether the compensatory trunk movement of stroke survivors can be decreased by force and visual feedback during reaching tasks; and (2) Whether one of these feedback modalities is more effective in reducing compensatory trunk movement.

Methods

Participants

Fifteen participants were recruited (Figure 1) from stroke recovery groups, the research group's website, and from the community. Table 1 provides a summary of participants' demographics. A previous controlled trial[11] that investigated the reduction of stroke survivors' trunk compensation using trunk restraint provided the rationale for the chosen sample size. Participants provided written consent and the study was approved by the Clinical Research Ethics Board.

Clinical Assessment

Baseline impairment and compensation assessments were administered by occupational therapists to determine the clinical characteristics of the participants (Table 1). The upper-extremity (UE) subsection of the Fugl-Meyer Assessment (FMA)[12] was utilized to measure UE motor impairment. The Reaching Performance Scale (RPS)[13] was used to assess level of participant compensation when reaching forward.

Experimental Design and Randomization

The trial used a crossover design; all participants experienced both treatments, and the order of the treatments was randomized. To reduce order effects, participants were randomly allocated (computerized pseudo-random number generator[a]) to start with visual or force feedback (Figure 1). Participants were first stratified according to FMA impairment scores (moderate to severe <50, and mild >= 50[5,14]) to ensure group balance, and then randomly allocated to the two treatment groups in blocks of two. Included in the final analysis were eight participants allocated to start with visual feedback, and seven with force feedback. Figure 2 details the experimental procedure.

Experimental Setup

The integrated system (Figure 3) consisted of two JACO[b] (Ver. 2, 6DOF) robotic arms, a Kinect[c] (Ver. 2) motion tracking camera and a personal computer. The system was controlled through a custom LabVIEW[d] program that displayed the reaching task on a monitor. Participants sat on a chair with at least 75% of their thighs resting on the seat, and a backrest and footrest adjusted to keep their hips and knees flexed at 90°.

Experimental Task

Participants were instructed to move two virtual cursors (Figure 4) representing each of their hands towards a target, and stay inside target bounds for 1 second. To move the cursors, participants performed symmetrical bimanual reaching movements from their hips to their knees (without touching their thighs), while holding two robotic device handles (Figure 3). Moving the robots required minimal resistance, as both robot arms were under admittance control[15] (robot sensed applied force and moved in the same direction). After every trial, participants returned to their initial calibrated position. If participants were unable to hold the robots' handles, they were provided with a wrist splint and a strap.

The movement of the cursors was only mapped to the anterior/posterior movement of participants' hands, and the robotic devices were capable of moving in two directions (up/down and forwards/backwards), video in appendix. Participants were told that moving up/down would not affect the task, and that they should aim to move their hands at a constant height above, and close to, their thighs.

The distance to the virtual target (90% of hip-knee distance) was calibrated by asking participants to move their unaffected hand from their hips to their ipsilateral knee. Before the session started, participants were asked to push as hard as possible, with the robotic arms stationary, to ensure that the maximum torque that they could exert was above the maximum force feedback that they would receive (9.5 Nm based on robots' torque limits). This torque was equivalent to the force required to hold a 1.23 kg object. Pilot studies had shown that this force is easily perceived by healthy participants. To ensure that stroke participants could sense the force, all participants confirmed during familiarization trials that they could feel how the force changed as they compensated with their trunk.

The robotic arms provided force feedback when the Kinect motion tracking camera detected that the participant showed anterior trunk displacement during a reaching movement. The feedback adjusted the minimum torque required to move the robotic arms. This type of feedback was chosen because it provided a safety advantage; the robots would not move unless the participants actively moved them, whereas a purely resistive force acting in the opposite direction of motion could harm the participant if they released the robots' handles. Up to the first 30 mm of compensation, participants did not receive feedback, as they were considered to be within the "normal" threshold of healthy compensation[3]. After this threshold, the force feedback was proportional to the amount of trunk compensation (Figure 5), and saturated at 50% of the average compensation each participant exhibited at baseline, minus the healthy compensation. The *desired* compensation was then set to 50% to promote achievable improvement in a short-term intervention. Our study involved only one training session, as a result, the desired compensation value was set to a static value. However, for interventions with multiple sessions, this value could be adjusted by researchers after every session to adapt to the current progress of their participants.

The visual feedback operated using the same algorithm as the force feedback (Figure 5), and was represented as red ink filling up the virtual cursors, similar to a thermometer filling up, and proportional to the amount of trunk compensation (Figure 4). In this condition, participants also moved the cursors using the robotic arms, but the force feedback was turned off. This visual display was chosen because: it did not add a new element to the screen (avoiding adding to the users' cognitive load), participants would already be familiar with this type of symbol, and it did not require detection of color change, which would be an issue for color-blind people.

Data Analysis

All kinematic variables analyzed were measured during the Baseline, Post Visual and Post Force trials, in which participants were not receiving feedback. The motion data were obtained from the Kinect and JACO arms at ~30 Hz. The data were then resampled at a constant rate (25 Hz), and low-pass filtered (6 Hz[16]). If any of the Kinect's data points were inferred or not tracked, they were removed from the motion log. The Kinect's spine-shoulder and shoulder joints have been reported to have an average accuracy of ~10 (SD:10) mm with high correlation (0.99), when compared to a gold standard motion capture system[17]. The capabilities of the camera were deemed sufficient to capture trunk compensation from stroke survivors, as their displacements tend to be 30 mm or more[3].

The primary outcome was trunk displacement (anterior displacement of the Kinect's spine-shoulder joint). Secondary outcomes included: Trunk Rotation: angle between the vector created from the left to the right shoulder joints, and the frontal plane (positive angles indicate counterclockwise rotations); Index of curvature: measure of the straightness of the hands' path towards the target in the *Y* and *Z* (superior/inferior and anterior/posterior) directions. The index was defined as the ratio of the hands' path and a straight line. A value of 1 would represent a perfectly straight path; Root Mean Square (RMS) Error in *Y* and *Z*: measure of bimanual symmetry between the hands' movement. This error was computed as the difference between the hands' position at every iteration of the program, and the RMS error of these values was calculated to obtain the final result. Smaller errors indicated more symmetrical movements; Time: measured from the moment participants were presented with the reaching task to the end of the trial; Post-Test Questionnaire: administered at the end of the study to investigate the experience of the participants and the usability of the system using the System Usability Scale[18].

Statistical Analysis

To investigate whether there were any differences between visual and force feedback to reduce compensation, an Analysis of Covariance (ANCOVA) was employed with a within-subject factor of treatment (Visual or Force), a between-subjects factor of group (start with Visual or Force), and the baseline measurements used as a covariate. To elucidate whether force and/or visual feedback reduced trunk compensation, the percentage gains (percent change from baseline to post measurements) were compared against a mean value of 0 using a one-sample t-test. When data violated parametric assumptions, the non-parametric Sign-Test was employed. For post-hoc tests, the p values were adjusted using the Bonferroni-Holm correction[19]. 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]. Significance level was set at $p < 0.05$.

Results

When comparing visual against force feedback (Table 2, left), for all outcome measures, all of the main effects and interactions of the ANCOVA were not statistically significant ($p > 0.05$).

The only exception was the Left Index of Curvature where the interaction between treatment and baseline was significant (p = .001), which would invalidate the results from the ANCOVA's significant treatment effect (p = .002) for this measure. Thus, for the outcome measures employed in this study, there is no evidence that one feedback method is more effective.

When investigating if visual and force feedback reduced trunk compensation from baseline (Table 2, right), a significant (p = 0.004) large effect (0.99 and 0.89, respectively) was observed for both methods. Individual results are presented in Table 3. For visual feedback: 8/15 participants reduced their compensation by more than 50%, 10/15 by more than 30%, and 2/15 increased their compensation by less than 33%. For force feedback: 8/15 participants reduced their compensation by more than 50%, 8/15 more than 30%, 3/15 increased their compensation by less than 30%. This evidence suggests that augmented visual and force feedback can reduce trunk compensation in hemiparetic stroke survivors. For all other measures, the differences were not statistically significant. Post-Test questionnaire results are presented in the appendix.

Discussion

Both visual and force feedback decreased trunk compensation exhibited by stroke survivors after a session of reaching trials with augmented feedback provided in these modalities. When comparing force with visual feedback to reduce trunk compensation we did not find any significant differences. In addition, when asked if receiving visual or force feedback reduced how much they moved their trunk, the majority of participants agreed (93.3% and 100%, respectively). This suggests that regardless of the modality of augmented feedback, participants use this information to correct their movement in a similar manner. However, studies with larger samples should be conducted to confirm this hypothesis. The question of which feedback medium is most effective for UE rehabilitation remains unanswered[21,22]. These augmented feedback modalities offer advantages for unsupervised, remote, or intensive rehabilitation, as they do not require a therapist to physically restrain the individual or provide feedback in real-time; the system employed in this study was composed of commercially available products that could be integrated to provide rehabilitation outside of a research/rehabilitation setting. The lack of a physical constraint could provide additional benefits, as clients could make a conscious choice about controlling their trunk movement[9], which is something that a physical constraint could impede. With the physical guidance provided by the trunk restraints, the clients might not actively plan/program their trunk movements, which could inhibit important efferent and afferent information necessary for creating the internal models of the movement[23].

The augmented feedback utilized in this study has the potential to be provided at different frequencies during UE rehabilitation exercises, offering a variable schedule of reinforcement. Inversely, the continuous nature of the feedback provided by trunk restraints could be detrimental for motor learning; the "guidance hypothesis" states that practicing movements with constant feedback can make the participant dependent on the feedback, hindering independence[24]. However, for stroke survivors who show severe motor impairment with very limited trunk control, trunk restraint might be the only safe and viable option. As these individuals recover trunk control, and internal representations of movement are acquired, rehabilitation should move toward augmented feedback exercises, progressing to an eventual removal of feedback in a graded manner.

In our study, six participants with greater UE motor impairment (FM $\leq$ 38) struggled to complete the force feedback condition due to UE weakness. These participants' affected hands had to be strapped, taped, or supported with a wrist brace, to hold onto the robots' handles or/and keep their wrist in a neutral position while they pushed through the force. Conversely, there were participants who found visual feedback less helpful, as it was easier to ignore, did not add any resistance to the movement, or was harder to understand. In the post-test questionnaire, 46.7% of participants responded that they would prefer to receive both feedback conditions, 26.7% only visual, and 26.7% only force. These observations, combined with the finding that there was not a statistical difference between employing visual or force feedback, suggest that there may not be an "ideal" feedback modality that works for every stroke survivor. We should instead use technology to provide feedback in an individualized manner, working to find the most suitable modality for an individual's impairment level, recovery stage, and learning style. Moreover, varying or combining the feedback medium could be most effective for rehabilitation. By varying feedback type throughout exercises, we could prevent clients from relying on a particular source of information to correct their movements. Varying feedback in a random schedule ensures novelty, which is important for retention and transfer of motor learning[25]. Gaming rehabilitation systems show great potential, as they can provide feedback through different modalities[26]. In addition, the setting in which rehabilitation occurs should be considered, as visual feedback could be easier and more cost-effective to implement using devices that are already available in the home (i.e., television, computer monitor), and force feedback may be more suitable in clinics or hospitals where larger, more costly devices can be acquired.

In this study we did not investigate whether a simple verbal instruction to avoid compensatory movement would effectively decrease compensation. To mitigate this limitation, we employed the same number of repetitions (60) and a similar experimental procedure as a previous stroke rehabilitation controlled trial[11], in which investigators compared a verbal instruction vs. a trunk restraint group on a unimanual physical reach-to-grasp task. The number of participants (14) and the samples were similar; however, our participants were on average older and more impaired (FMA scores). The previous study found that verbal instructions did not reduce compensation, while trunk restraint did. Our percent change values for visual (-41%) and force (-42%) feedback were on average superior to their trunk restraint values by 10% and 11%, respectively, and by 31% and 32% when compared to their verbal control condition. These results suggest that on average, augmented visual and force feedback in a short-term intervention could provide similar results to trunk restraint, and superior results to verbal instructions. Moreover, a study[10] investigating the use of visual feedback and operant conditioning in five video game rehabilitations sessions reduced relative compensation (trunk lateral lean) compared with no feedback. Further, a longer-term (twelve sessions) bimanual/unimanual intervention[9] study investigating the use of auditory feedback vs. trunk restraint found both methods improved scores on the RPS, FMA, and the Wolf Motor Function Test. Our results, combined with these previous studies, suggest that augmented feedback could be employed as a complement or substitute to trunk restraint.

Study Limitations

The current pilot study investigated the effects of feedback in only a single session. Longitudinal studies should be conducted to explore the long-term effects of this intervention type. As kinematic data alone are not sufficient to confirm the clinical utility of augmented feedback for rehabilitation, future studies should examine whether the changes in movement seen with these feedback modalities correlate with increased functional performance and independence with activities of daily living. Our results had large standard deviations due to the heterogeneity of the sample in terms of motor function, as shown by the baseline FMA and RPS scores. Studies with larger samples would enable researchers to stratify participants to various groups based on motor impairment. This approach would allow researchers to draw stronger conclusions about the effects of augmented feedback on stroke survivors with different motor/functional abilities. In our study, some participants had to employ a wrist brace and/or strap to hold onto the robotic arm. Future studies should investigate alternate approaches to secure the hands while minimizing any potential effects to the participants' reaching performance. Finally, the force feedback that participants received was sensed through their upper limbs while holding the device's handles, which limits the generalization of these results to one sensing area of the body. It should be investigated if providing feedback cues directly to the trunk through a haptic or vibrotactile device could result in improved results to the ones presented in this work.

Conclusions

Both visual and force feedback appear to be effective candidates for reducing trunk compensation of stroke survivors. It remains to be established whether one of these feedback modalities is more efficacious. Using technology to provide real-time feedback that works best for each individual may be more effective than using one modality for all individuals who exhibit trunk compensation post-stroke.

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of gaming and social media applications for stroke and cerebral palsy upper limb rehabilitation. In: 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). Chicago, IL: 2014. p. 3602–5.

Suppliers

a. Sealed Envelope Ltd., 501 Clerkenwell Workshops, 27-31 Clerkenwell Close, London EC1R 0AT, United Kingdom.

b. Kinova Robotics, 6110, rue Doris-Lussier, Boisbriand (Quebec), J7H 0E8, Canada.

c. Microsoft Corporation, One Microsoft Way, Redmond, WA, 98052-6399, United States of America.

d. National Instruments Corporation, 11500 N Mopac Expwy, Austin, TX, 78759-3504, United States of America.

Table 1. Demographic and clinical data for stroke participants. Baseline impairment and compensation assessments were administered by occupational therapists

	Sex	Age	Height (cm)	DH BS	HS	Type of Stroke	Time since stroke (months)	FMA (max. 66)	RPS (max. 36)
S-01	M	58	178	R	L	H	38	28	5
S-02	F	80	156	R	L	H	47	45	23
S-03	M	58	178	L	R	H	24	38	13
S-04	M	65	170	R	R	I	48	46	26
S-05	F	45	172	R	L	I	26	55	31
S-06	F	58	157	R	R	I	180	32	14
S-07	F	71	152	R	L	H	13	43	28
S-08	M	48	170	L	L	I	31	29	5
S-09	M	83	170	R	L	I	11	19	9
S-10	M	69	175	R	R	I	114	34	NA
S-11	F	55	163	R	L	I	79	47	33
S-12	M	69	168	R	L	I	69	46	29
S-13	M	62	178	R	R	I	22	58	34
S-14	M	77	178	R	R	I	31	59	29
S-15	M	66	178	R	R	I	132	15	7
Average		**64.27**	**169.53**				**57.67**	**39.60**	**20.42**
SD		**11.02**	**8.66**				**49.17**	**13.36**	**11.02**

DHBS=Dominant hand before stroke, FMA =Fugl-Meyer Assessment, HS=Hemiparetic side, H=Hemorrhagic, I=Ischemic, L=Left, NA= Not Available, R=Right, RPS=Reaching Performance Scale

Table 2. Comparison Between Post Force and Post Visual variables (left), Percentage Change from Baseline to Post Measurements (right).

	Post Visual vs. Post Force		
	Baseline	**Post Visual**	**Post Force**
Trunk Displacement (mm)	119.2 (71.7)	69.8 (73.1)	68.7 (64.6)
Trunk Rotation (°)	-1.2 (6.0)	-2.2 (7.2)	-1.5 (6.5)
Time (s)	7.4 (4.2)	5.5 (1.5)	5.7 (2.1)
Index Curv. Left YZ	1.3 (0.67)	1.1 (0.24)	1.1 (0.15)
Index Curv. Right YZ	1.5 (1.4)	1.1 (0.13)	1.2 (0.23)
RMS Z (mm)	22.4 (11.4)	31.1 (29.0)	29.7 (23.9)
RMS Y (mm)	31.6 (25.2)	40.6 (25.4)	35.9 (20.3)

	Percentage change from Baseline to Post measurements	
	Post Visual	**Post Force**
Trunk Displacement (%)	**-45.6 (45.8)**** ***t(14)=-3.86 p=.004 d=0.99 Int: -70.9,-20.2***	**-41.1 (46.1)**** ***t(14)=-3.46 p=.004 d=0.89 Int: -66.7,-15.6***
Trunk Rotation (%)	17.5 [-19.5, 170.2]	-0.45 [-21.8, 76.2]
Time (%)	-10.4 [-36.9, -2.3]	-14.1 [-28.0, -4.3]
Index Curv. Left YZ (%)	-0.14 [-5.9,6.5]	1.5 [-4.7,4.0]
Index Curv. Right YZ (%)	-3.2 [-6.2, 3.1]	0.16 [-5.4, 5.1]
RMS Z (%)	13.4 [-4.9, 36.3]	9.4 [-12.0, 58.5]
RMS Y (%)	27.0 [-9.3, 121.2]	19.2 [-8.8, 80.1]

Mean (SD). Median [1st and 3rd Quartiles]. Significant results are bolded (* P<0.05, **P<0.01). Analysis of Covariance employed to compare Post Visual vs. Post Force (left), T-Test and Sign-Test (values reporting median and quartiles) for percentage change comparisons (right). *d=Cohen's d. Int: 95% confidence interval. p=p value. RMS=Root Mean Square. t(degrees of freedom)=t value.*

Table 3. Individual results for trunk compensation

	Baseline (mm)	Post Visual (mm)	Post Force (mm)
S-01	251.6	238.8	1.8
S-02	37.5	-11.5	-11.2
S-03	139.7	184.6	181.3
S-04	74.4	72.4	71.2
S-05	91.3	18.6	44.6
S-06	119.8	8.0	23.0
S-07	154.8	16.7	121.4
S-08	184.4	45.8	83.7
S-09	114.3	103.7	90.7
S-10	189.9	72.4	66.3
S-11	50.3	25.2	19.0
S-12	65.7	76.7	73.4
S-13	45.5	14.1	10.3
S-14	33.5	21.8	38.8
S-15	235.6	159.8	217.1
Average	**119.2**	**69.8**	**68.7**
SD	**71.7**	**73.1**	**64.6**

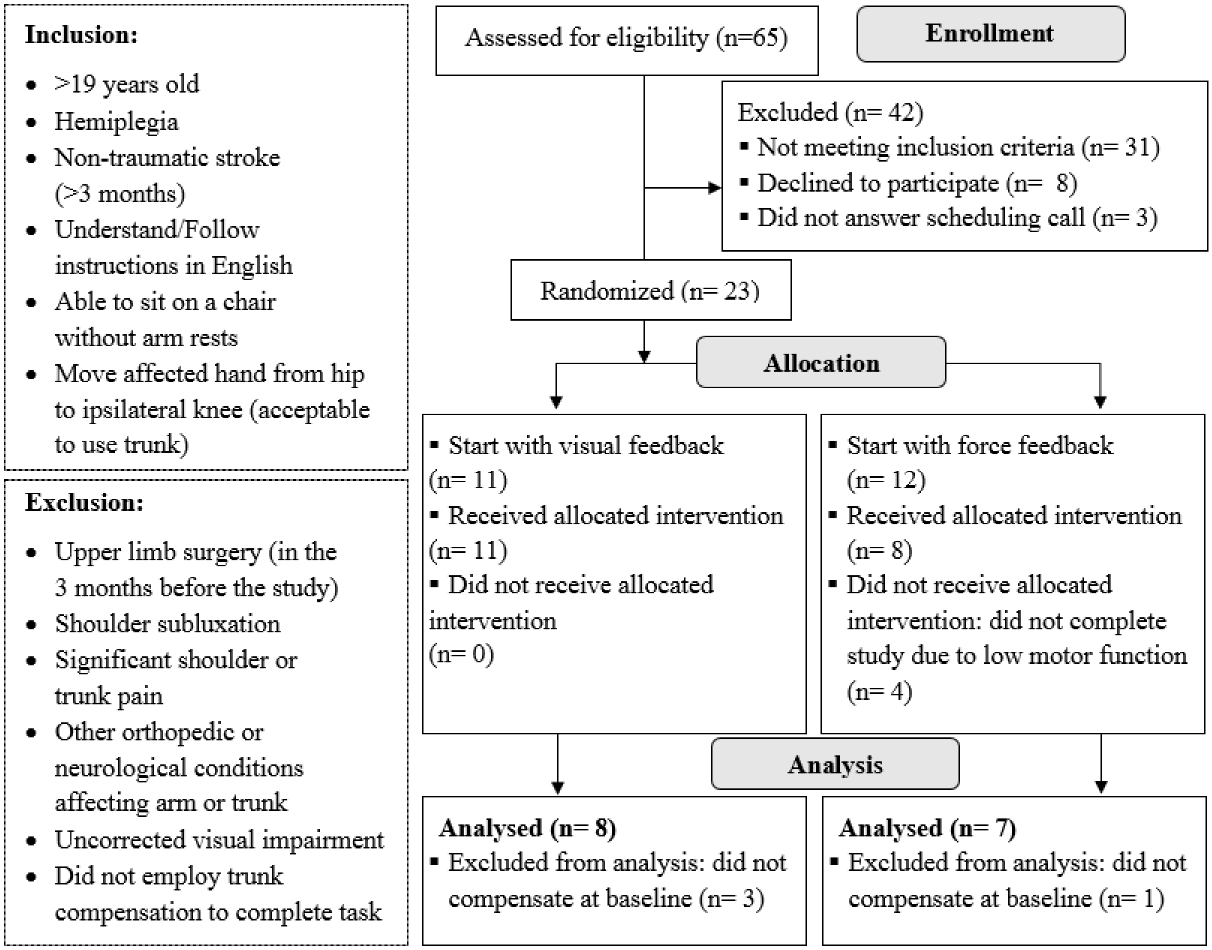


Figure 1. Recruitment and Allocation (January-April 2016). The enrollment, allocation, and assignment of participants were conducted by the first author. The allocation sequence was stored on a digital file, and the participants were not aware of their allocation until after the familiarization with the system was completed and the baseline measurements were taken.

Figure 2. Experimental Design. Number of trials in parenthesis. Condition A: Visual Feedback, Condition B: Force Feedback. Participants did not receive feedback in any of the post trials. This was a low-risk study, with fatigue being the only possible harm. To reduce fatigue, participants received 1 minute rests after every 15 trials, and were able to rest between targets if requested. An average of 17.3 (6.8) minutes elapsed between the end of the first feedback condition and the start of the second one.

Figure 3. Experimental Setup. Participants moved the robotic devices while completing the reaching task (displayed in the computer monitor). In addition, a motion tracking camera was placed in front of the participant to monitor trunk compensation.

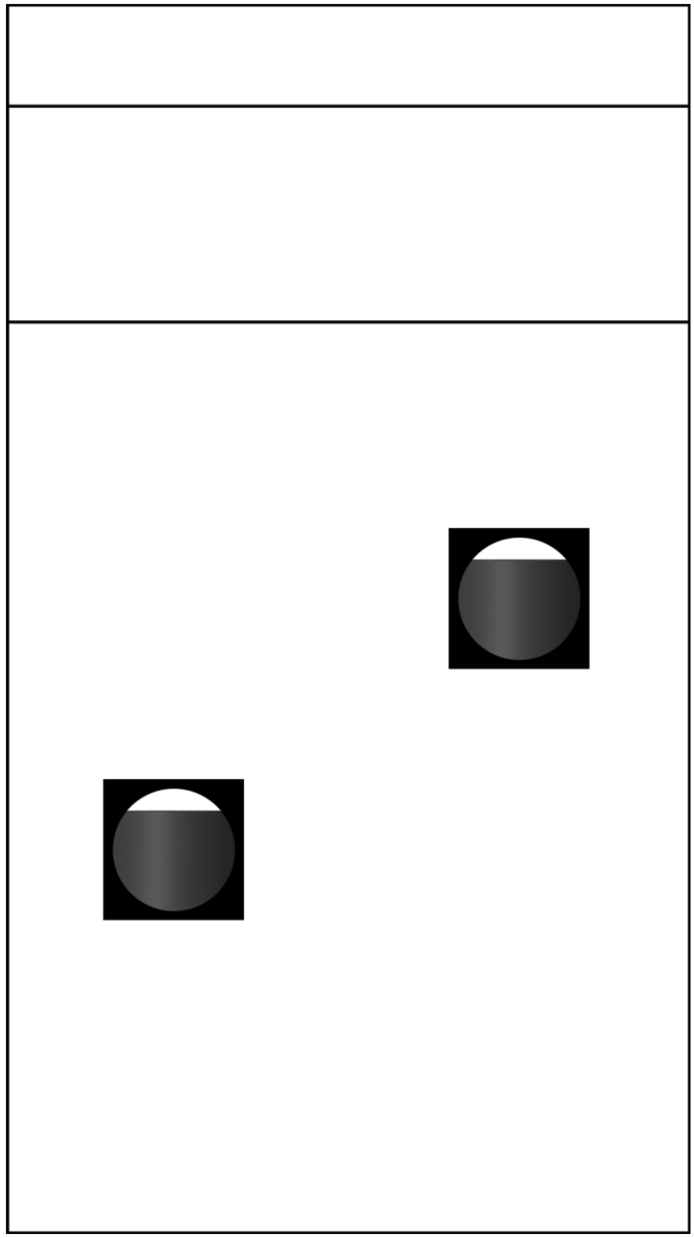
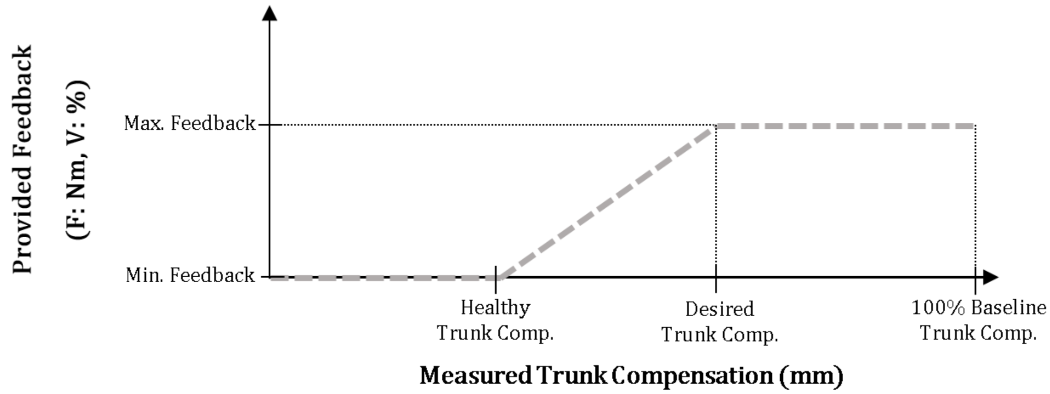


Figure 4. Virtual Reaching Task with Visual Feedback Active. Participants needed to move both cursors inside the target (two horizontal lines, top of the figure) to complete one trial. When not receiving visual feedback the cursors would be empty (white).



$$Provided\ Feedback = m(Measured\ Trunk\ Comp.) + b$$

$$m = \frac{(Max.\ Feedback - Min.\ Feedback)}{(Desired\ Trunk\ Comp. - Healthy\ Trunk\ Comp.)}$$

$$b = Min.\ Feedback - m\ (Healthy\ Trunk\ Comp.)$$

$$Healthy\ Trunk\ Comp. = 30mm$$

$$Desired\ Trunk\ Comp. = 0.5 * (Baseline\ Trunk\ Comp. - Healthy\ Trunk\ Comp.)$$

Figure 5. Provided Feedback Calculation.

F: Force Feedback. F Max. Feedback: 9.5 Nm. F Min. Feedback: 1Nm.

V: Visual Feedback. V Max. Feedback: 100%. V Min. Feedback: 0%.