# Assessment of dynamic balancing responses following perturbations during slow walking in relation to clinical outcome measures for high-functioning post-stroke subjects

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## Abstract

Background: Generating appropriate balancing reactions in response to unexpected loss of balance during walking is important to prevent falls. The purpose of this study was to assess dynamic balancing responses following pushes to the pelvis in groups of post-stroke and healthy subjects.

Methods: Forty-one post-stroke subjects and forty-three healthy subjects participated in the study. Dynamic balancing responses to perturbations triggered at heel strike of the left or right leg, directed in the forward, backward, inward and outward directions during slow treadmill walking were assessed. Responses of the healthy group provided reference values used to classify responses of the post-stroke group into two subgroups; one within the reference responses (“inside” subgroup) and the other that falls out (“outside” subgroup). A battery of selected clinical outcome measures (6-Minute Walk Test, 10-Meter Walk Test, Timed-Up-and-Go test, Four Square Step Test, Functional Gait Assessment, Functional Independence Measure and One-legged stance test) was assessed for the post-stroke group to examine whether any of these outcome measures could discriminate between both subgroups.

Results: Both subgroups of stroke subjects were comparable in terms of clinical outcome measures but their capacity to react to unexpected loss of balance during walking differed considerably. The “inside” subgroup was able to appropriately modulate centre-of-pressure and ground-reaction-force both under the impaired and non-impaired leg. The “outside” subgroup showed limited modulation capacity under the impaired leg; their responses utilised a stepping strategy in which the non-impaired leg was placed such as to make a longer step (forward perturbation), to make a shorter step (backward perturbation) or to make a cross-step (outward perturbation). Consequently, peak centre-of-mass displacements following perturbations were significantly higher in the “outside” subgroup compared to the “inside” subgroup. Responses in both subgroups following inward perturbations did not differ considerably. One-legged stance test showed the largest potential to discriminate between both subgroups of stroke subjects.

Conclusions: The One-legged stance test could be used to obtain an indication of the abilities of each particular post-stroke subject to counteract an unexpected loss of balance. This may be relevant in

clinical practice for the identification of post-stroke subjects who could benefit from perturbation-based training.

## Full Text

Due to technical limitations, full-text HTML conversion of this manuscript could not be completed.

However, the manuscript can be downloaded and accessed as a PDF.

## Figures

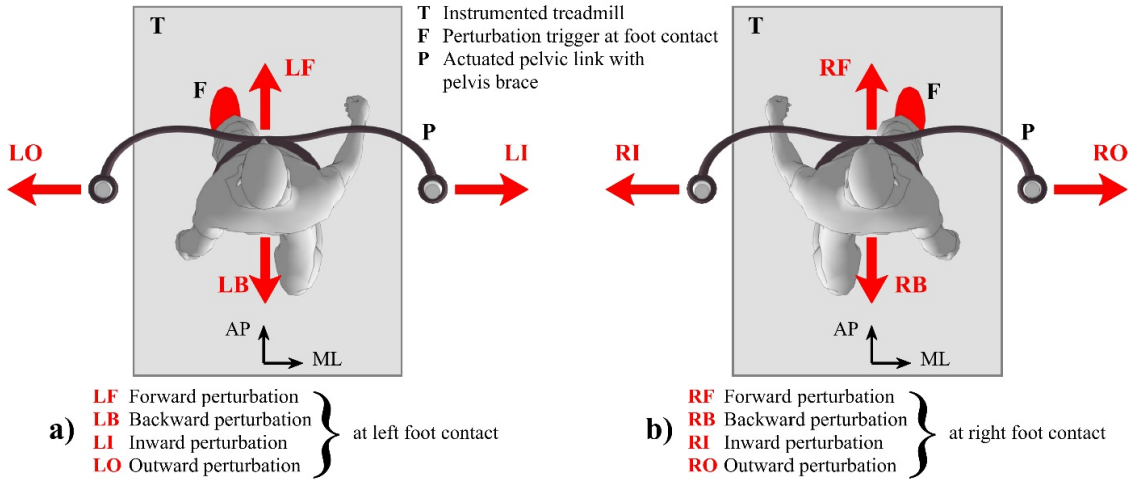


Fig. 1. Experimental setup for assessing balance responses after perturbations applied to pelvis. Perturbations were applied in forward, backward, inward, outward directions and were triggered at either a) left or b) right heel contact.

Figure 1

Experimental setup for assessing balance responses after perturbations applied to pelvis. Perturbations were applied in forward, backward, inward, outward directions and were triggered at either a) left or b) right heel contact.

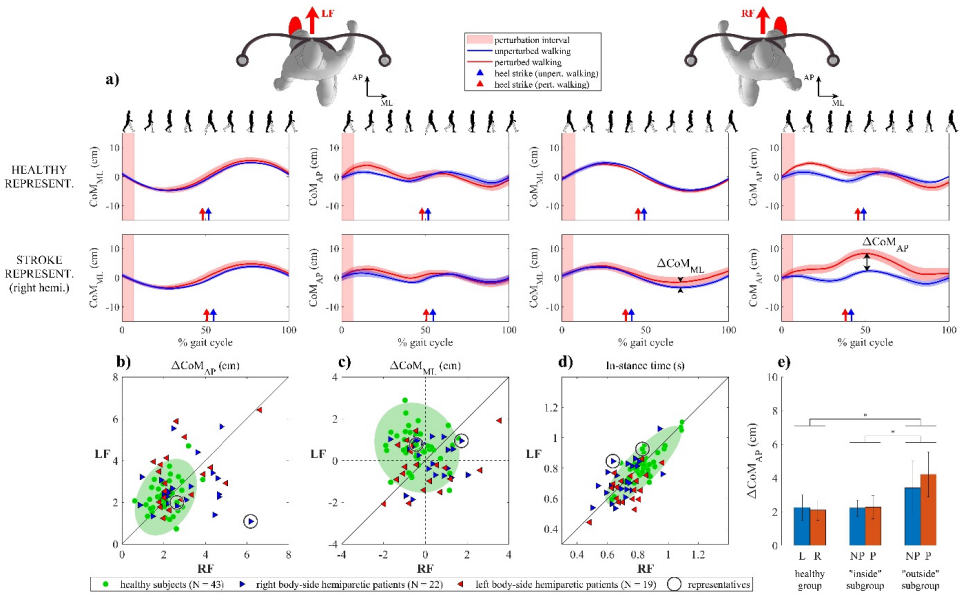


Fig. 2. Kinematics following forward perturbation. a) $CoM_{AP}$ and $CoM_{ML}$ trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta CoM_{AP}$ shown for all subjects along with covariance error ellipse. c) $\Delta CoM_{ML}$ shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the $\Delta CoM_{AP}$ averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

Figure 2

Kinematics following forward perturbation. a) CoMAP and CoMML trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔCoMAP shown for all subjects along with covariance error ellipse. c) ΔCoMML shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the ΔCoMAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

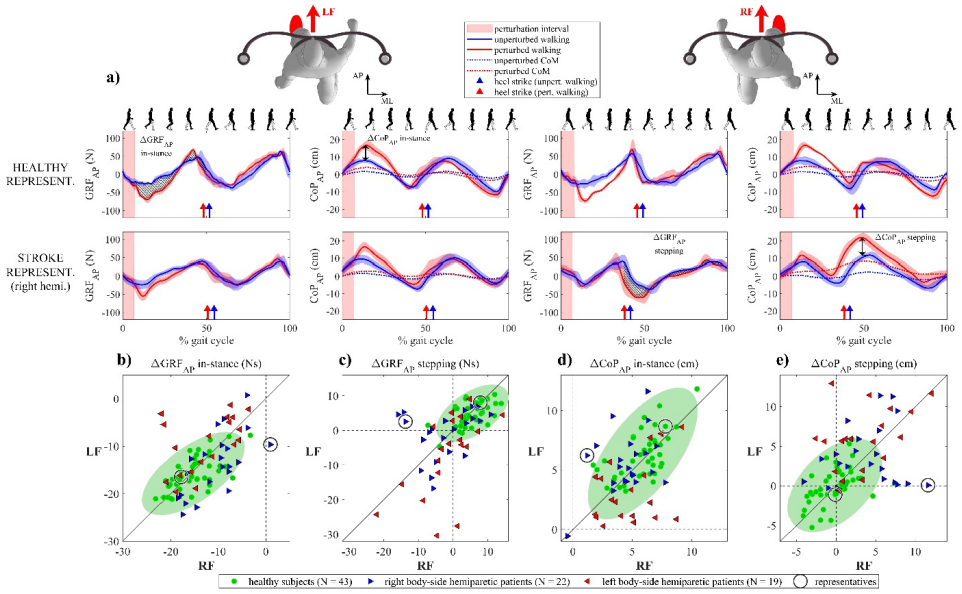


Fig. 3. Kinetics following forward perturbation. a) $GRF_{AP}$ and $CoP_{AP}$ signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta GRF_{AP}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) $\Delta GRF_{AP}$ in "stepping" period of response shown for all subjects along with covariance error ellipse. d) $\Delta CoP_{AP}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) $\Delta CoP_{AP}$ in "stepping" period of response shown for all subjects along with covariance error ellipse.

Figure 3

Kinetics following forward perturbation. a) GRFAP and CoPAP signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) Î”GRFAP in â€œin-stanceâ€ period of response shown for all subjects along with covariance error ellipse. c) Î”GRFAP in â€œsteppingâ€ period of response shown for all subjects along with covariance error ellipse. d) Î”CoPAP in â€œin-stanceâ€ period of response shown for all subjects along with covariance error ellipse. e) Î”CoPAP in â€œsteppingâ€ period of response shown for all subjects along with covariance error ellipse.

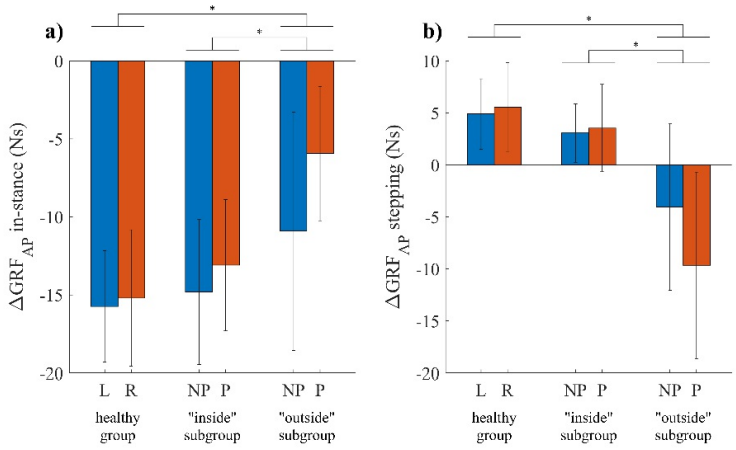


Fig. 4. Kinetics following forward perturbation. Group mean values and standard deviations for the ΔGRFAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. b) "stepping" period of response.

Figure 4

Kinetics following forward perturbation. Group mean values and standard deviations for the ΔGRFAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) “in-stance” period of response. b) “stepping” period of response.

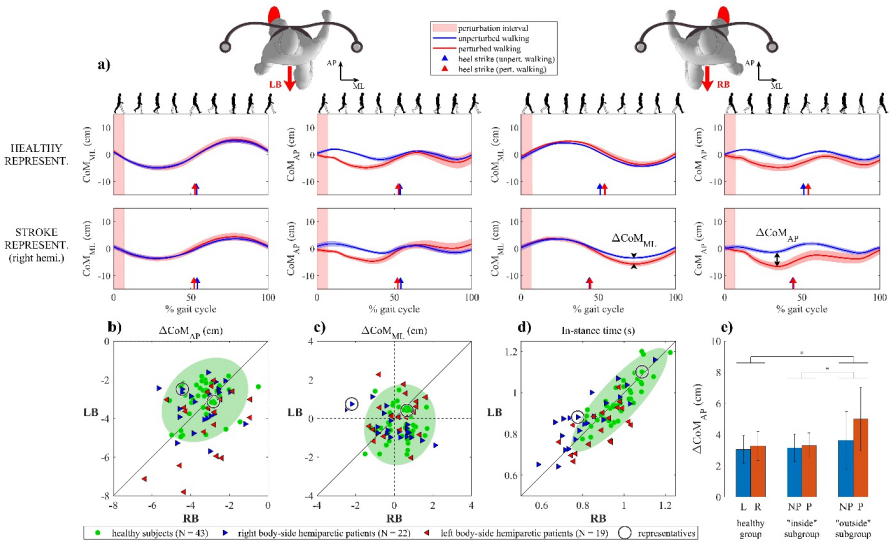


Fig. 5. Kinematics following backward perturbation. a) $CoM_{AP}$ and $CoM_{ML}$ trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta CoM_{AP}$ shown for all subjects along with covariance error ellipse. c) $\Delta CoM_{ML}$ shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the $\Delta CoM_{AP}$ averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

## Figure 5

Kinematics following backward perturbation. a) CoMAP and CoMML trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔCoMAP shown for all subjects along with covariance error ellipse. c) ΔCoMML shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the ΔCoMAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

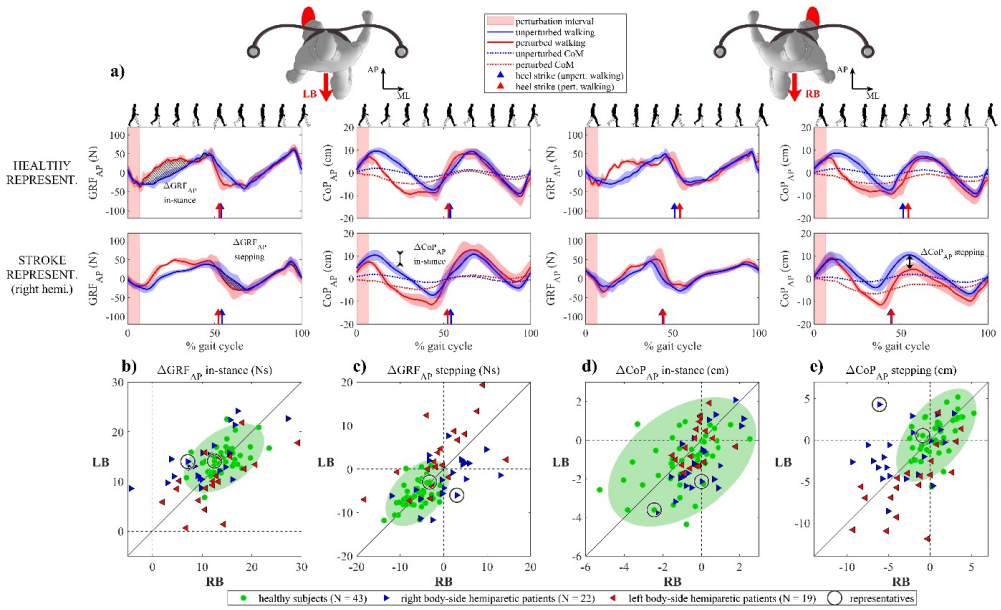


Fig. 6. Kinetics following backward perturbation. a) $GRF_{AP}$ and $CoP_{AP}$ signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta GRF_{AP}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) $\Delta GRF_{AP}$ in "stepping" period of response shown for all subjects along with covariance error ellipse. d) $\Delta CoP_{AP}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) $\Delta CoP_{AP}$ in "stepping" period of response shown for all subjects along with covariance error ellipse.

Figure 6

Kinetics following backward perturbation. a) GRFAP and CoPAP signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔGRFAP in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) ΔGRFAP in "stepping" period of response shown for all subjects along with covariance error ellipse. d) ΔCoPAP in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) ΔCoPAP in "stepping" period of response shown for all subjects along with covariance error ellipse.

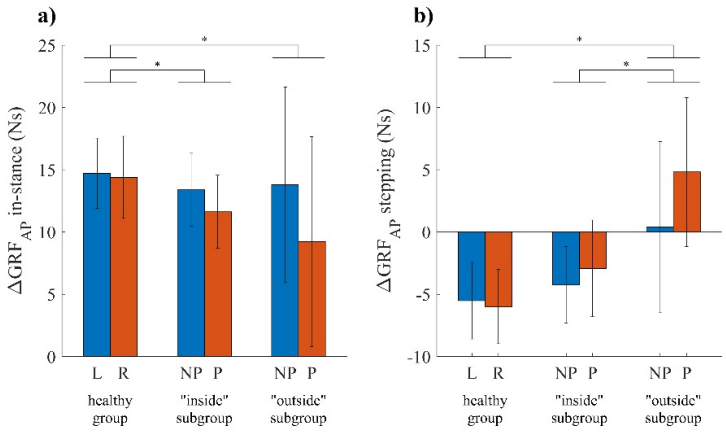


Fig. 7. Kinetics following backward perturbation. Group mean values and standard deviations for the ΔGRFAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. b) "stepping" period of response.

Figure 7

Kinetics following backward perturbation. Group mean values and standard deviations for the ΔGRFAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. b) "stepping" period of response.

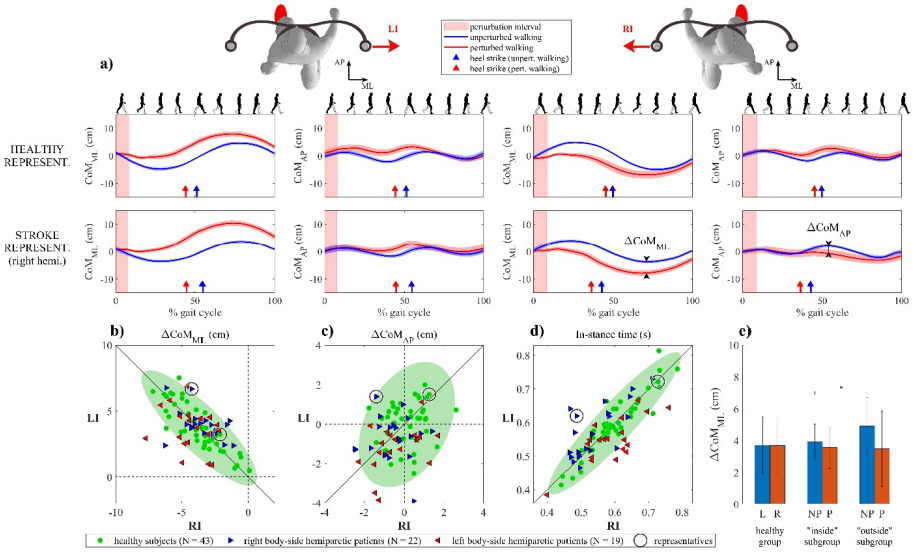


Fig. 8. Kinematics following inward perturbation. a) $CoM_{AP}$ and $CoM_{ML}$ trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta CoM_{AP}$ shown for all subjects along with covariance error ellipse. c) $\Delta CoM_{ML}$ shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the $\Delta CoM_{AP}$ averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

Figure 8

Kinematics following inward perturbation. a) CoMAP and CoMML trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔCoMAP shown for all subjects along with covariance error ellipse. c) ΔCoMML shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the ΔCoMAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

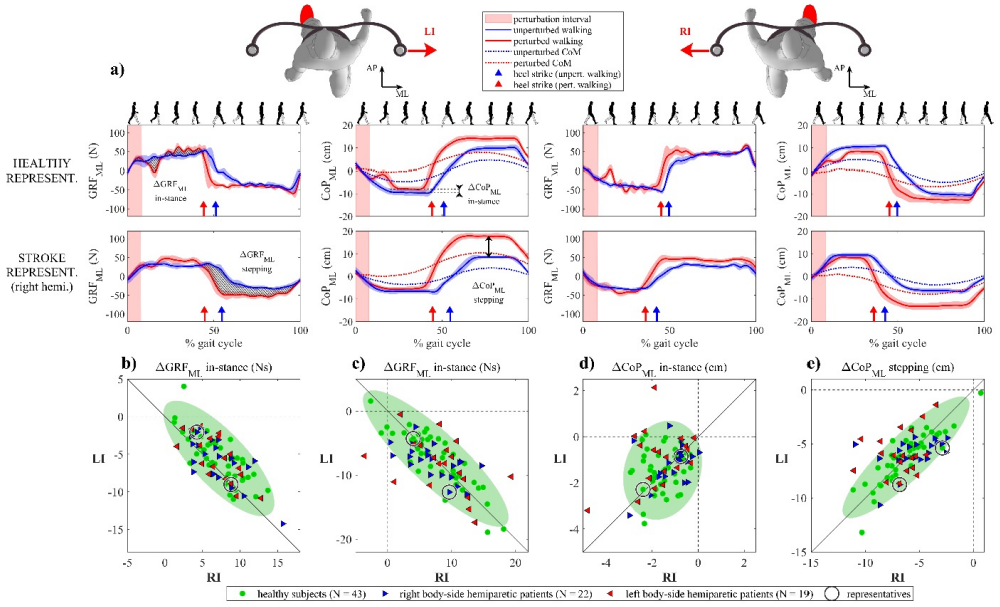


Fig. 9. Kinetics following inward perturbation. a) $GRF_{ML}$ and $CoP_{ML}$ signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta GRF_{ML}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) $\Delta GRF_{ML}$ in "stepping" period of response shown for all subjects along with covariance error ellipse. d) $\Delta CoP_{ML}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) $\Delta CoP_{ML}$ in "stepping" period of response shown for all subjects along with covariance error ellipse.

Figure 9

Kinetics following inward perturbation. a) GRFML and CoPML signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔGRFML in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) ΔGRFML in "stepping" period of response shown for all subjects along with covariance error ellipse. d) ΔCoPML in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) ΔCoPML in "stepping" period of response shown for all subjects along with covariance error ellipse.

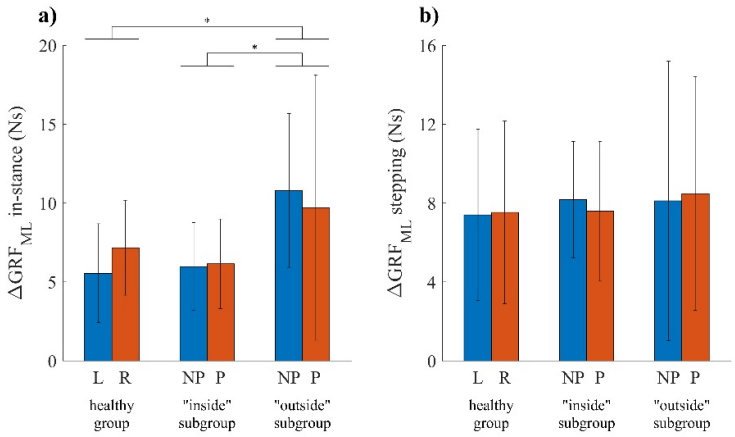


Fig. 10. Kinetics following inward perturbation. Group mean values and standard deviations for the $\Delta GRF_{ML}$ averaged for perturbations occurring at heel contact of left (L) or right leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. B) "stepping" period of response. Note that a sign for blue bars has been changed to facilitate visual comparison.

Figure 10

Kinetics following inward perturbation. Group mean values and standard deviations for the ΔGRFML averaged for perturbations occurring at heel contact of left (L) or right leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. B) "stepping" period of response. Note that a sign for blue bars has been changed to facilitate visual comparison.

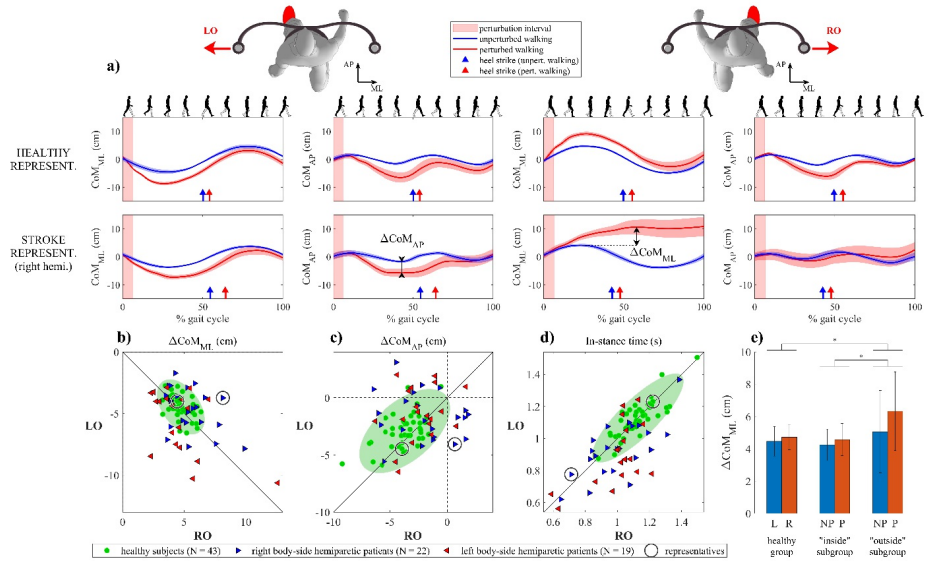


Fig. 11. Kinematics following outward perturbation. a) $CoM_{AP}$ and $CoM_{ML}$ trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta CoM_{AP}$ shown for all subjects along with covariance error ellipse. c) $\Delta CoM_{ML}$ shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the $\Delta CoM_{AP}$ averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

Figure 11

Kinematics following outward perturbation. a) CoMAP and CoMML trajectories (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔCoMAP shown for all subjects along with covariance error ellipse. c) ΔCoMML shown for all subjects along with covariance error ellipse. d) In-stance time shown for all subjects along with covariance error ellipse. e) Group mean values and standard deviations for the ΔCoMAP averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons.

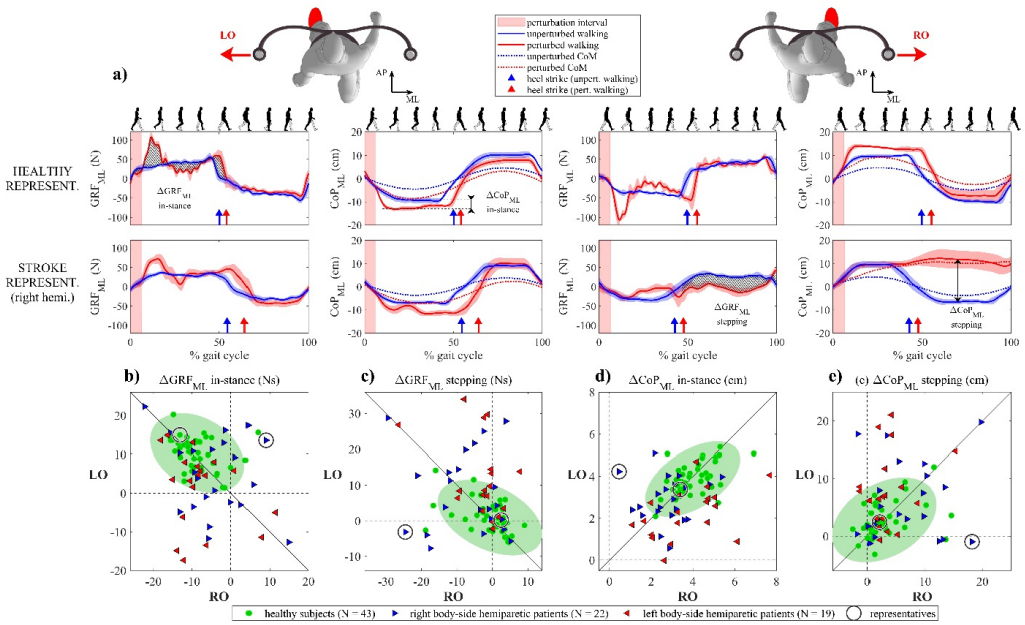


Fig. 12. Kinetics following outward perturbation. a) $GRF_{ML}$ and $CoP_{ML}$ signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) $\Delta GRF_{ML}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) $\Delta GRF_{ML}$ in "stepping" period of response shown for all subjects along with covariance error ellipse. d) $\Delta CoP_{ML}$ in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) $\Delta CoP_{ML}$ in "stepping" period of response shown for all subjects along with covariance error ellipse.

Figure 12

Kinetics following outward perturbation. a) GRFML and CoPML signals (mean values and standard deviations) for representative healthy subject and representative right-sided hemiparetic subject over one gait cycle. b) ΔGRFML in "in-stance" period of response shown for all subjects along with covariance error ellipse. c) ΔGRFML in "stepping" period of response shown for all subjects along with covariance error ellipse. d) ΔCoPML in "in-stance" period of response shown for all subjects along with covariance error ellipse. e) ΔCoPML in "stepping" period of response shown for all subjects along with covariance error ellipse.

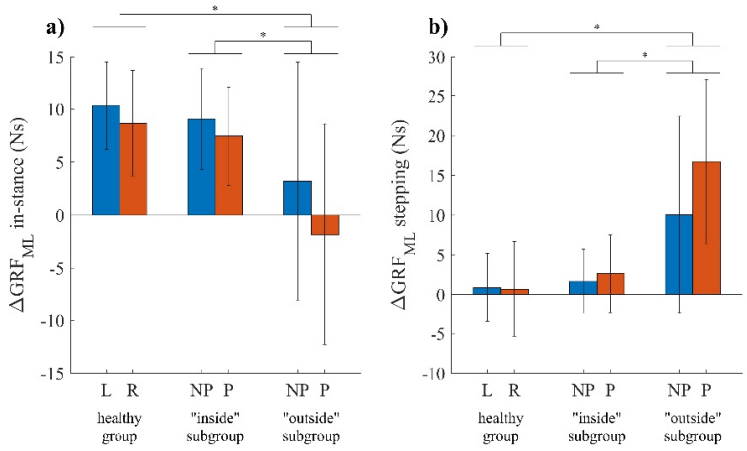


Fig. 13. Kinetics following outward perturbation. Group mean values and standard deviations for the ΔGRFML averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) "in-stance" period of response. b) "stepping" period of response. Note that a sign for red bars has been changed to facilitate visual comparison.

Figure 13

Kinetics following outward perturbation. Group mean values and standard deviations for the ΔGRFML averaged for perturbations occurring at heel contact of left (L) or right (R) leg for group of healthy subjects and for perturbations occurring at heel contact of non-paretic (NP) or paretic (P) leg both subgroups of stroke subjects. Asterisk (*) indicates a significant difference between groups in Bonferroni post-hoc paired comparisons. a) “in-stance” period of response. b) “stepping” period of response. Note that a sign for red bars has been changed to facilitate visual comparison.

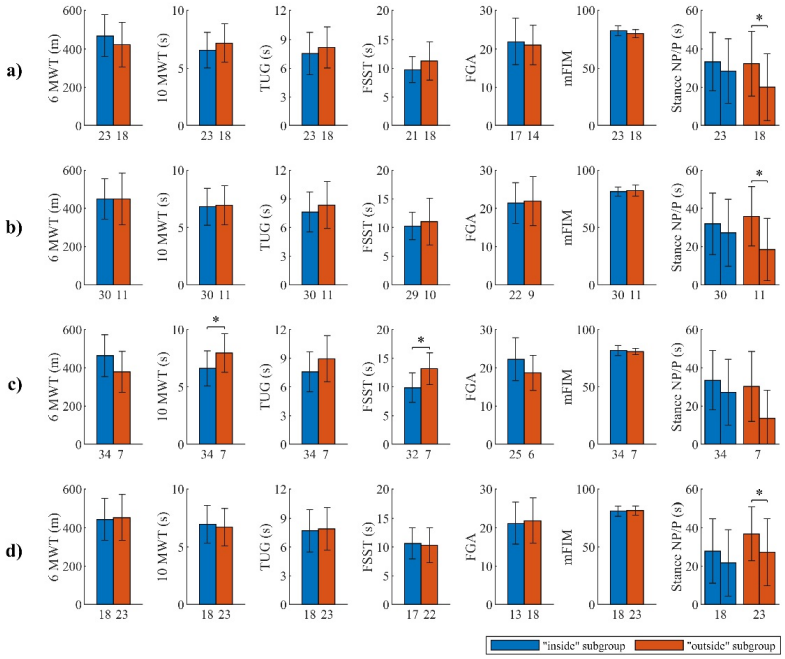


Fig. 14. Group mean values and standard deviations of the clinical outcome measures: 6MWT, 10MWT, TUG, FSST, FGA, mFIM and One-legged Stance Test for "inside" and "outside" subgroups of post-stroke subjects grouped according to covariance error ellipses for each perturbation direction separately: a) forward, b) backward, c) inward and d) outward. The numbers below each bar indicate the number of post-stroke patients in each of the subgroups. Asterisk (*) indicates a significant difference between the subgroups.

Figure 14

Group mean values and standard deviations of the clinical outcome measures: 6MWT, 10MWT, TUG, FSST, FGA, mFIM and One-legged Stance Test for “inside” and “outside” subgroups of post-stroke subjects grouped according to covariance error ellipses for each perturbation direction separately: a) forward, b) backward, c) inward and d) outward. The numbers below each bar indicate the number of post-stroke patients in each of the subgroups. Asterisk (*) indicates a significant difference between the subgroups.