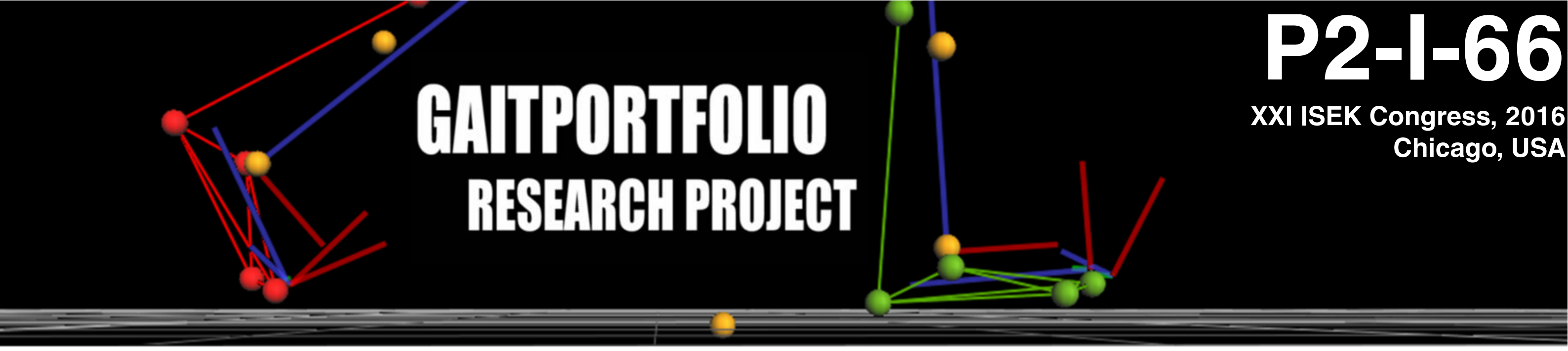

Arm swing during healthy gait: a verbal dual-task attenuates right arm swing

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Introduction: Arm swing asymmetry during walking increases when an additional cognitive task is introduced.[1,2] While older individuals and patients with certain neurological disorders are more susceptible, the characteristics and mechanism of this effect are unclear. We hypothesised that this response is lateralised, and that a Stroop task – thought to primarily subsist on left hemisphere structures – would cause a reduction in arm swing only on the right and be exacerbated by increasing age and task difficulty.

Methods: Eighty-three healthy subjects (three age groups; 18-39, 40-59 and 60-80) walked on a treadmill at a comfortable speed while performing a congruent ($Stroop_{easy}$) and incongruent Stroop ($Stroop_{hard}$) word/colour naming task. Gait parameters, including an index of arm swing asymmetry (ASI) based on 3D kinematic wrist trajectory lengths, were recorded. A positive ASI indicates proportionally larger arm swing amplitudes on the left and vice versa. Participants also completed a lateral preference inventory questionnaire.[3] Trial means of gait parameters were analysed using a linear mixed model with post-hoc t-tests.

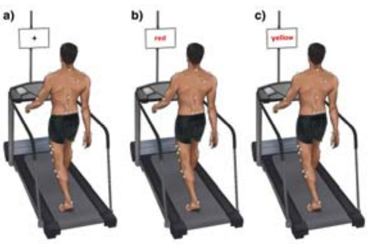

Figure 1. Experimental setup. For the normal walking condition, subjects walked on an instrumented treadmill while fixating a black cross (a). They then performed two Stroop colour-naming task (see methods) of differing difficulty. Image (b) shows the simpler task in which word and colour stimuli are congruent. In the more difficult, incongruent task (c) word and colour are discordant.

Results: Compared to normal walking (NW), ASI values increase significantly during both dual-task conditions in the 40-59 age group (NW: -0.28±2.03, $Stroop_{easy}$: 5.87±3.38, $Stroop_{hard}$: 9.19±3.31; p=≤0.048) and in both tasks in older adults (NW: -0.68±2.07, $Stroop_{easy}$: 8.31±3.70, $Stroop_{hard}$: 15.16±3.80; p≤0.009; **Figure 2**) compared to NW. In adults over 60, this shift was driven by significantly reduced wrist trajectories ($Stroop_{easy}$: -13.1%, $Stroop_{hard}$: -22.1%; p≤0.049; **Figure 3**) and maximal shoulder anteversion (mean±SD; NW: 4.35±10.07°, $Stroop_{easy}$: 1.21±10.35°, $Stroop_{hard}$: -0.54±11.62°; p≤0.032) under both dual-task conditions. In this older group, right maximal elbow flexion also reduced significantly between the NW and $Stroop_{hard}$ conditions (NW: 53.69±11.49°, $Stroop_{hard}$: 48.34±8.08°; p = 0.012; **Figure 4**). No changes were seen on the left. A sub-analysis showed that males in all age groups exhibited significant, positive shifts in ASI in the $Stroop_{hard}$ task, while a similar effect was only seen in women over 60 (**Figure 5**). There were no correlations between the degree of behavioural lateralisation and change in ASI under cognitive load.

Age Group	n	Age (years)	Percent female	Weight (kg)	Height (cm)	Percent right-handers	Walking speed (kmh-1; med± IQR)	25FWT (s)	10MWT (s)	6MWT (m)	Arm length asymmetry index
18 – 39	31	28.6±4.9	51.6	71.3±15.5	175±9	93.5	4.3±0.9	3.28±0.44	4.30±0.61	726±80	-0.56±2.16
40 – 59	23	47.5±8.1	52.0	73.5±13.0	172±8	96.0	4.0±0.8	3.50±0.47	4.62±0.63	701±83	-0.86±1.89
60 – 80	29	67.8±4.5	62.1	65.5±10.0	168±9	96.6	3.7±0.6	3.76±0.60	4.91±0.82	671±100	-0.26±2.35

Table 1: Characteristics of the included participants, separated into age groups. All data presented as means with standard deviation except where indicated. IQR; interquartile range, T25FW; timed 25-foot walk, 10MWT; 10-metre walk test, 6MWT; 6-minute walk test.

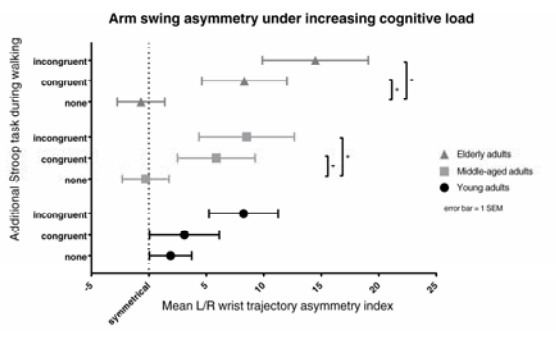

Figure 2. Arm swing asymmetry under increasing cognitive load. Wrist trajectory asymmetry index is calculated using the left and right 3D wrist centre trajectories, with left dominance resulting in a positive value and vice versa. ASI is given as the mean value per gait cycle over a trial of 45 seconds (approximately 42 gait cycles at 4kmh-1). SEM; standard error of the mean. Statistical significance was determined using a linear mixed model with post-hoc t-tests. P values are corrected for multiple pairwise within-age group comparisons using the Bonferroni method.

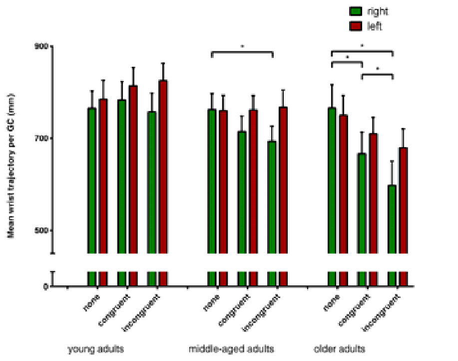

Figure 3. Absolute wrist trajectory length. Three-dimensional wrist joint centre trajectories for younger, middle-aged and older adults during NW and during a congruent and an incongruent Stroop dual-task. GC; gait cycle. Error bars indicate 1 standard error of the mean. Statistical significance was determined using a linear mixed model with post-hoc t-tests. P values are corrected for multiple pairwise within-age group comparisons using the Bonferroni method.

Interpretation: These findings suggest that human arm swing is at least partially generated by cortical inputs which are susceptible to interference from concomitant cognitive tasks. In men and older women, increased cognitive load during the primarily verbal, predominantly left hemisphere Stroop task causes a reduction in arm swing on the right. This paucity of swing amplitude is characterised by decreased flexion at the shoulder and elbow with preserved extension, consistent with previous findings that the upper limb flexors are under more direct supraspinal control.[4]

A gender sub-analysis showed that the effect of aging on ASI shift was specific to females (**Figure 5**). This unexpected and pronounced resistance to right arm swing attenuation in pre-menopausal women may be due to oestrogen-mediated plasticity and attendant redundancy in the prefrontal cortex (PFC), where oestrogen receptors are plentiful and oestradiol increases dendritic spine density in primates.[5,6] In women, there is an oestrogen-related enhancement of cognitive control and inhibition of inappropriate representations while susceptibility to the Stroop task is ameliorated by oestrogen treatment after the menopause.

The left PFC - activated during active stepping, treadmill walking and the Stroop task[7,8] - is thus a strong candidate for the site of the cognitive-motor interference underlying the observed ASI shifts in men and older women. Whether this is related to dual-task performance strategies or a tendency for females to be less strongly lateralised is unclear, although lateralisation did not predict the degree of arm swing attenuation.

Conclusion: Reduction in right arm swing appears to be the norm in humans performing a motor-cognitive dual-task, confirming a prominent role of the brain in arm swing behaviour. In older adults, asymmetry is characterised by reduced arm protraction, suggesting that upper limb flexors are under more direct supraspinal control and susceptible to interference. Overcoming this interference appears to be a trait unique to younger females and implies significant gender differences at the top of the hierarchical chain of locomotor control. Applying this paradigm to patients with PD, subcortical stroke and SCI may permit further insights into the control of arm movements in human locomotion.

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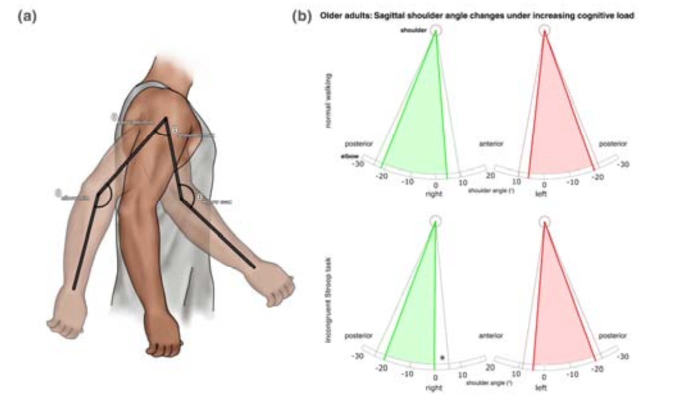

Figure 4. a). Sagittal gait cycle mean joint angle maxima and minima based on the approach used by Roggendorf *et al.*[9] b) Sagittal shoulder angle changes during normal walking and under increased cognitive load (incongruent Stroop task) in older adults walking on a treadmill. Diagrams represent the right (green) and left (red) mean sagittal shoulder angle maxima and minima (thick lines) per gait cycle with associated single standard deviations (dotted lines). A significant decrease in shoulder flexion in the incongruent Stroop task is indicated by *. Elbow flexion was also reduced under increased cognitive load, with preserved extension (not shown; see results section).

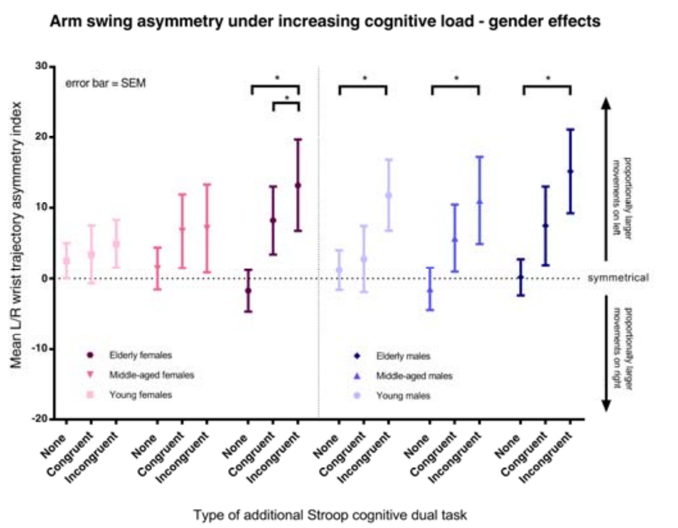

Figure 5. Arm swing asymmetry under increasing cognitive load – gender effects. Wrist trajectory asymmetry index is calculated using the left and right 3D wrist centre trajectories, with left dominance resulting in a positive value and vice versa. ASI is given as the mean value per gait cycle over a trial of 45 seconds (approximately 42 gait cycles at 4kmh-1). SEM; standard error of the mean. Statistical significance was determined using a linear mixed model with post-hoc t-tests. P values are corrected for pairwise within-group comparisons to NW only using the Bonferroni method.

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