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Postural control strategies in young adults during dual tasking in different stance positions

BEV 3901 Master's thesis

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Abstract

In everything we do, we need to have control over our body's position in space. Traditionally, postural control is assumed to need few attentional resources that are directed instead to other ongoing tasks. Changes in postural control while conducting a concurrent cognitive task compared to a baseline level of performance is referred to as dual task interference. The aim of this study was to investigate the effect of dual tasking on postural control with the following specific question: Does the type and magnitude of postural control movements depend on the difficulty of concurrent cognitive tasks, the level of difficulty of stance position, or both? Participants performed three different difficulty levels of counting (counting backwards in 1s, 3s and 7s) during two different challenges to postural control (standing with feet hip-width apart or close together). Data collected consisted of force plate measurements and 3-dimensional motion capture. Analyses focused on Centre of Pressure (CoP) and Principal Component Analysis (PCA), respectively. PCA identified four important categories of movements: postural movements, breathing movements, head movements, and multi-segment movements. Stance position, but not dual tasking affected the CoP measures. In contrast, PCA was capable of detecting significant task effects on principal velocity and principal acceleration, and some task effects on principal movements. Furthermore, there was a tendency for higher order PCs to be more sensitive to changes in task than lower order PCs. The latter, especially ankle and hip movements dominate CoP measures. In conclusion, stance position influenced postural control as indicated by changes in CoP measures, but the latter were not sensitive to cognitive dual tasks. In contrast, PCA clearly distinguished single task from different levels of counting, even from single task to simple backwards counting in 1s, especially with respect to principal velocity and acceleration.

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Introduction

1.1 Postural Control

In everything we do, it is fundamental to have control over our body's position in space. The control of the body's position in space for the purpose of balance and orientation has been defined as postural control (Woollacott & Shumway-Cook, 2002). Postural control is needed in every task, and for this purpose we have an orientation component and a stability component. The orientation component refers to the ability to maintain a good relationship between the body segments, and between environment and body in tasks (Winter, 1995). The stability component, also called balance, refers to the ability to control the center of mass (COM) in relationship to the base of support (Shumway-Cook & Woollacott, 2012). Postural control in adults is often thought to be a reflex or automatically controlled task, a response to proprioceptive, visual, and vestibular information (Bouisset & Zattara, 1981) because the body uses little or minimal attentional resources to stay in equilibrium. However, regulating posture involves cognitive as well as sensory processes (Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1993), as indicated by so-called dual task interference, changes in postural control due to conducting a simultaneous attentionally demanding task (Woollacott & Shumway-Cook, 2002).

1.2 Dual task paradigm

Traditionally, it has been assumed that controlling balance needs few attentional resources. However, by looking at changes in postural control while conducting another attentionally demanding task, referred to as *dual task interference,* suggests that postural control requires significant attentional resources. It also appears that attentional requirements are not constant, but vary depending on the postural task, the individual's balance abilities and the age of the individual (Woollacott & Shumway-Cook, 2002). There is an effect of dual task, if any change above the baseline level of performance occurs, when comparing the primary task in isolation with concurrent performance of another task (secondary task). This can indicate that a competition for central processing is taking place (Andersson, Yardley, & Luxon, 1998). There are two outcomes of interest in dual task studies. The first is the possible effect of balance on the cognitive task performance. The second outcome is the effect of cognitive task on balance functioning.

Dual task interference has been explained by two primary theories. *Capacity theory,* views dual task interference as resulting from having to share a limited set of information processing (i.e. attentional) resources. In this case, a degraded performance is observed on one or both tasks when processing demands of two simultaneously executed tasks exceed the attentional capacity. The second theory, *bottleneck theory*, proposes a serial nature of the dual-task process regarding single channel filtering, where only one piece of information is processed at a time. This will favor the prioritized task as the nervous system will delay information processing related to the non-prioritized task and therefore the performance for this task will be reduced (Fraizer & Mitra, 2008). A study by Lajoie et al. (1993) tested young adults on an auditory reaction time task while sitting, standing bipedal and with reduced base of support, and walking. Reaction time was fastest while sitting and slowed down in the standing position, becoming even slower in reduced base of support, while reaction time was slowest in walking. This suggests that an increase in balance requirements demands more attention to secure postural control and therefore competing for limited resources (capacity theory). For the bottleneck theory, Kerr et al. (1985) were among the first to demonstrate the attentional demands of postural control during stance. By testing the difficulty of stances Kerr and colleagues showed interference with a spatial (visual) memory task, which presumably shared the same central processing. There was an increase of errors in the spatial memory task compared to the non-spatial memory task when performing the tandem-stance, but no changes in postural sway. sway. The difficulty of this stance may cause prioritization of postural control and therefore degrade the performance of the cognitive task. It has been hypothesized that this is due to the postural and visual spatial task competing for the same neural visual processing channels. In contrast, a study by Mylène C Dault, Frank, and Allard (2001) tested the working memory, which includes a visuo-spatial component, the articulatory loop and the central executive system. They found differences in postural sway, namely increased frequencies and a decrease in amplitude, but no differences between the types of working memory tasks. There were also no interactions between level of cognitive task and the different difficulty levels of the stances, bipedal and tandem stance. A previous study by Pellecchia (2003) in which a compliant surface was used to eliminate the sensory information, demonstrated that increased difficulty of the cognitive task resulted in larger postural sway.

1.3 Methods to quantify postural control

Common to all of the above studies is the use of force plate and outcome measures derived from the Center of Pressure (CoP) displacement. Studies using displacement of CoP can lead to misevaluation of the quality of the balance-control system under static situations. In the way that increased and decreased CoP displacement can reveal age-related strategies or context-depended behaviours rather than good or bad postural task performance. (Lacour, Bernard-Demanze, & Dumitrescu, 2008). There are many approaches to quantify postural control movements during quiet stance. Direct measurements consist of the kinematics of specific joints or quantifying the sway angle of the center of mass (Gage, Winter, Frank, & Adkin, 2004; Sasagawa, Ushiyama, Kouzaki, & Kanehisa, 2009). Indirect measurements include quantification of the Center of Pressure (CoP) movement (Winter, Prince, Frank, Powell, & Zabjek, 1996) or the measurements of muscle activation involved in postural control (Dietz & Duysens, 2000). The combination of quantification of joint kinematics and measurements of the muscle activation of postural control movements has led to the definition of postural control strategies, i.e. ankle or hip strategy (Gatev, Thomas, Kepple, & Hallett, 1999; Winter et al., 1996). Ankle strategy refers to when ankle plantarflexors/dorsiflexors alone control the center of mass to keep it inside the base of support. Hip strategy refers to the medio-lateral control of the body, where the hip works as a load/unload mechanism and flexion/extension to control central of mass (Winter, 1995). The combination of ankle and hip strategy was earlier believed to provide a full explanation of postural control movements (Horak & Nashner, 1986), but more recent studies have shown that higher order, multi-segment movement strategies can explain additional elements of the postural control movements (Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007).

1.4 Principal Component Analysis

A study by Federolf, Roos, and Nigg (2013) used a different approach to analyze the multi-segmental postural movement strategies, by using principal component decomposition of marker coordinates. Because postural control movement amplitudes are typically small this method gives a good opportunity to analyze small motion amplitudes during quite stance. This method can identify, quantify and visualize postural strategies by splitting the complex, multi-segment movement into simple orthogonal, linear movement components. It has been suggested to call these linear movement components *Principal movements* (PMs) (Federolf, Reid, Gilgien, Haugen, & Smith, 2014). Federolf et al. (2013) analyzed quiet stance with different difficulties, such as bipedal, tandem and one-leg stance. Their findings support earlier studies that multi segment postural movement patterns should be considered. In more difficult stances, such as tandem and one-leg stance, larger numbers of principal movements are needed to capture 90% of the variance in posture. However, no study so far has applied principal component analysis (PCA) to quiet standing under dual task conditions, leaving the question open whether this method can be used to identify small amplitude adjustments to postural control while performing a second task.

1.5 Study aim

The above papers have looked at dual task interference using force plates with outcomes of CoP displacement. Federolf et al. (2013) used PCA to interpret postural strategies. To the best of my knowledge, there is no previous study that has combined these methods, using PCA to examine postural control strategies while conducting a concurrent task in different stances. Therefore, the aim of this study is to investigate the effect of dual tasking on postural control strategies using 2 different stances and 3 levels of difficulty in the cognitive task. The present project addresses the following specific question: Does the type and magnitude of postural movements depend on the difficulty of concurrent cognitive tasks, the level of difficulty of stances, or both?

2. Methods

2.1 Participants

Thirteen young adults, 6 men and 7 women (26,1 ± 3,5 years, 171,2 ± 12 cm height, 66 ± 9,9 kg) participated in this study. To be eligible to participate, they had to be between 18-35 years, healthy and no history of injury in the lower body during the past year. All participants were university students and were recruited in Trondheim. All participants signed a written consent form and a video consent form. The Regional Ethical Committee approved the study.

2.2 Equipment

A Kistler 9286BA force plate (600x400x35 mm) was placed in the middle of a laboratory and collected data at a sampling rate of 240 Hz. The system was calibrated before the first subject of the day arrived. OQUS Motion Capture System (Qualisys AB, Gothenburg, Sweden) was used to record the movements of the participants. Seven cameras were placed around the area where the participants were standing during the test. All the cameras were suspended from the roof. Sampling rate was 240 Hz, and all the cameras where calibrated prior to arrival of the first participant of the day. A digital video recorder was placed on the right side of participant to record sagittal view of the volunteers. Thirty-nine passive reflexive markers were placed on the subjects

39 passive reflexive markers were placed on the subjects, according to the “Plug in gait marker placement” (see Figure1). These were attached with double-sided tape to the participants according to the plug in gait marker placement (figure). The participants had tight clothing as possible, so the markers did not move in and between the trials. Marker distance error was <1.0 mm.

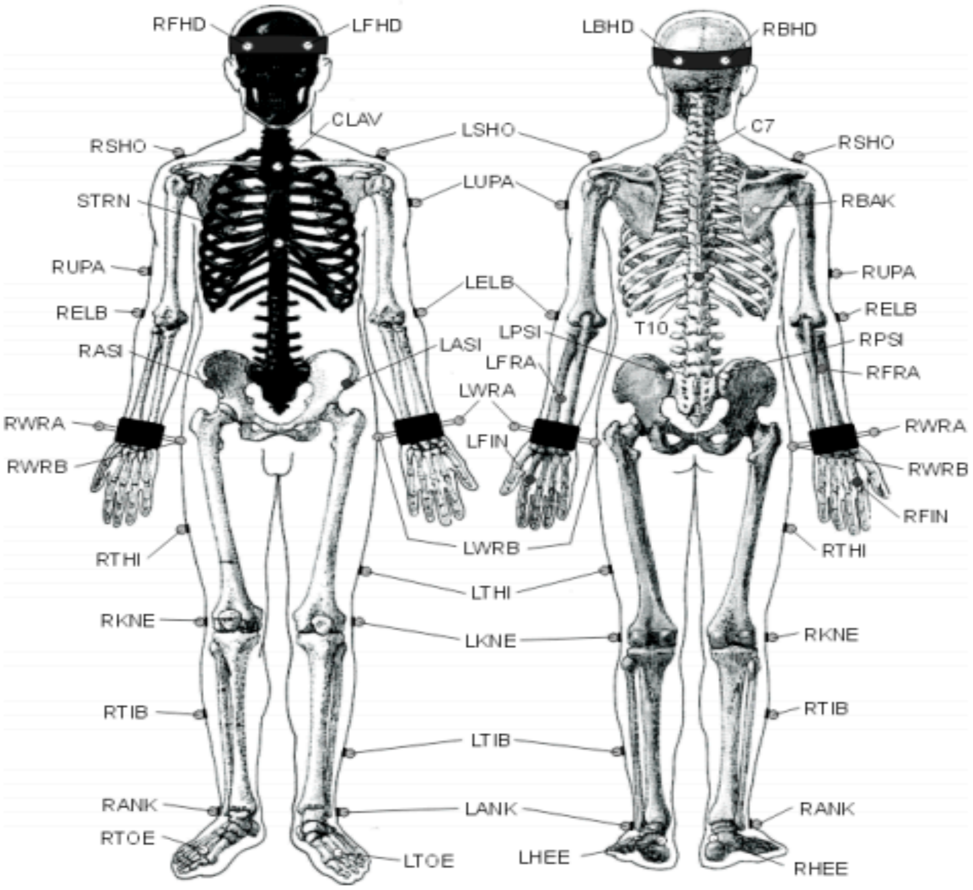

Figure 1: Marker placement according to the plug in gait marker set up, reprinted from ("Plug in Gait Marker Placement,").

2.3 Postural task

Participants were instructed to stand as still as possible with their hands hanging down beside their body during each trial. The participants conducted two different ways of standing: 1) Quite standing, in which the participants had to stand as still as possible with their feet hip-width apart. 2) Close feet as still as possible, in which the toes and heels were placed touching each other. All trials were completed barefooted.

2.4 Dual task

The cognitive task was counting backward in three different difficulty levels. The participants had to count backwards in steps of 1, 3 and 7. Starting numbers were varied between trials to avoid subjects repeating the same patterns. They subtracted with 1 from 150, 160 and 170, subtracting with 3 from 201, 214 and 224, and with 7 from 254, 262 and 278, respectively.

2.5 Procedure

The participants stepped on a 3.5-cm high, wooden platform placed in front of the force plate, which was on the same level as the force plate. Each trial started with, the subject receiving instructions about the specific condition and task of the trial. Upon a signal from the operator of the data collection system, the participants stepped onto the force plate into the specified posture (hip-wide or close feet) and started to count as soon as they felt they were standing correctly.

The participants went through 8 trials, each lasting for 120 seconds, 2 single task trials and 6 dual task trials. Each participant was tested individually. All trials were conducted in 2 blocks, first block were always the single task trials in 2 different standing positions. The second block included counting with 1, 3 and 7 in one of the standing positions, these trials were counterbalanced between participants. There was no feedback on the performance.

2.6 Data analysis

To avoid the movements due to stepping onto the force plate, the first 20s were removed from each trial. A period of 100 seconds, from 20s to 120s, was selected for further investigation. Missing marker data (e.g. due to occlusion) were reconstructed using an algorithm developed by Gløersen & Federolf (manuscript in preparation). Thus, in each trial 24001 time frames contained the 3D coordinates of 39 markers, which quantified the volunteer's postural movements during the 100s. The 39 3D-marker coordinates were interpreted as 117-dimensional posture vectors $\boldsymbol{p}(t_i)$. The 24001 $\boldsymbol{p}(t_i)$ quantify the entire movements of the subjects during the analysis period. Universal principal movements were calculated by employing a normalization technique, which allowed combining the posture vectors of all subjects into one common input matrice for the PCA. The normalization algorithm was designed to retain the variability between posture vectors created from postural movements in the input matrix for the PCA while minimizing the anthropometric differences between the subjects (Federolf et al., 2013).

In four steps the normalization was applied: 1) for each trial a mean posture vector, $\boldsymbol{p}_{mean}$ was calculated and subtracted from all posture vectors of this trial. 2) Then the vector norm, $d(t_i)$ of these centered posture vectors was calculated. 3) For the entire trial, all centered posture vectors were divided by the mean vector norm, d_{mean} (Federolf et al., 2013).

$$\boldsymbol{p}_{norm}(t_i) = (\boldsymbol{p}(\boldsymbol{t}_i)\text{-}\boldsymbol{p}_{\text{mean}})/\boldsymbol{d}_{\text{mean}}$$

4) The posture vectors were normalized by assigning the relative weight distribution (Plagenhoef, Evans, & Abdelnour, 1983) to the markers that constituted the posture vector.

Calculating a PCA on the normalized posture vectors $\boldsymbol{p}_{norm}(t_i)$ from all the subjects yielded eigenvectors, eigenvalues and a coefficient/score for each posture vector. The orthogonal eigenvectors indicate the direction of the largest variance of the posture vectors within the 117-dim posture space; the eigenvectors are usually called the principal component vectors $\boldsymbol{PC}_j$. The variance in the direction defined by each $\boldsymbol{PC}_{j,}$ is quantified by their associated eigenvalues EV_j. The $\boldsymbol{PC}_j$ are ordered according to their eigenvalues such that the lower order $\boldsymbol{PC}_j$ (small j) contain the largest movement components of the subjects. By projecting the posture vectors $\boldsymbol{p}(t_i)$ onto the principal component $\boldsymbol{PC}_j$ coefficients $c_j(t_i)$ were obtained, which quantify the progression of each one-dimensional principal movement component in time.

The i and j refer to the time frame (i= 1,...,24001) and the number of the principal component (j = 1,…,117). Time series were formed by the coefficients $c_j(t_i)$, from each subject during a postural control task, which allowed a quantitative analysis of the principal movement. Then each principal movement was projected back into the original posture space and revoking the normalization yielded posture vectors, $\boldsymbol{PM}_j(t_i)$, which could be graphically visualized as animated stick figures (Figure 2).

$$\boldsymbol{PM}_j(t_i) = \mathbf{p}_{\text{mean}} + a_j d_{mean} c_j(t_i)\boldsymbol{PC}_j$$

The amplification factor a_j (in the current study typically 30) facilitated a visual interpretation of the principal movement, whose range of motion would otherwise be too small to be noticed.

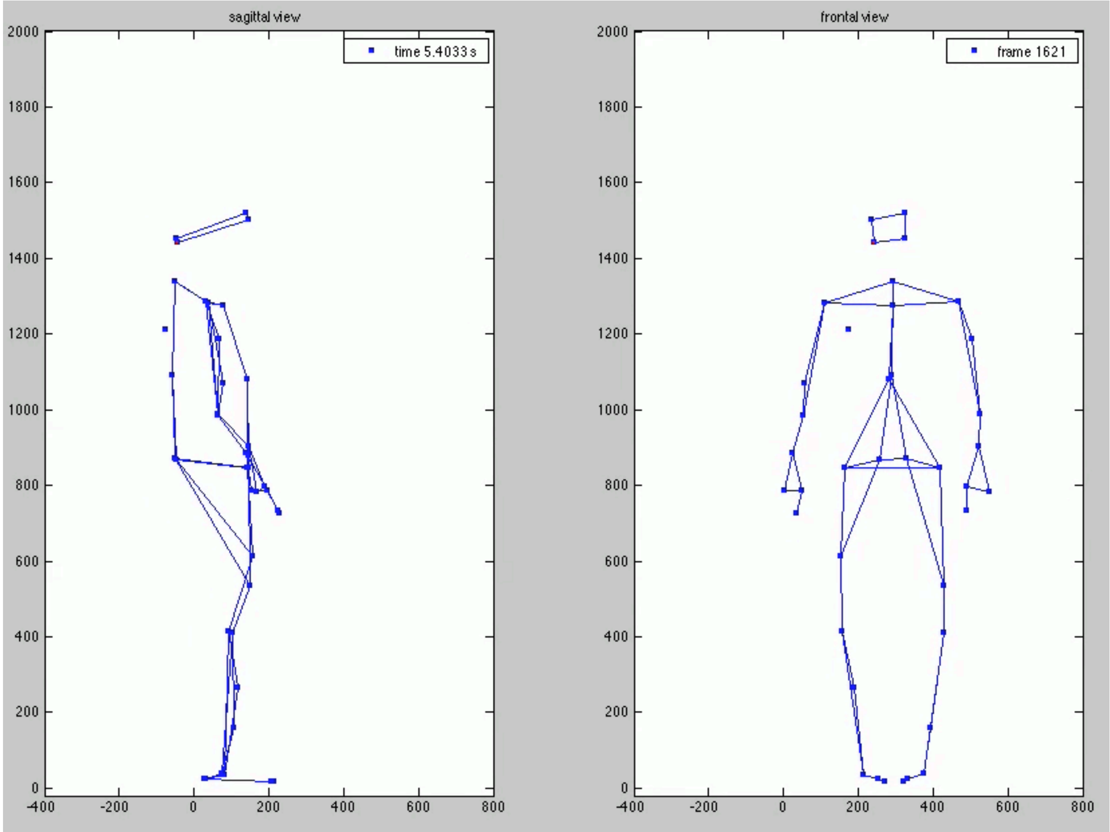

Figure 2: Screenshot of the stick figure from the videos of PMs.

To see how much PM_j contributed to the entire set of postural movement in all subjects, the eigenvalues EV_j were normalized by dividing each EV_j by the sum of all EV_j (Federolf et al., 2013).

Variables used to quantify postural movements

The first 15 PMs were evaluated. To see how much PM_j contributed to the entire set of postural movement in all subjects, normalized eigenvalues EV_j were calculated. They were normalized by dividing each EV_j by the sum of all EV_j (Federolf et al., 2013). The $\boldsymbol{PM}_j(t_i)$ represent specific postures as a function of time with the temporal evolution quantified by the associated $c_j(t_i)$. In order to understand postural control it is also interesting to calculate how fast the posture changes, i.e. a "postural velocity", and what acceleration produces the postural velocity, i.e. "postural acceleration". Since the $c_j(t_i)$ quantify the posture as a function of time, its first temporal differentiation, called "principal velocity (PV)" quantifies the speed of changes in posture, and its second differentiation, called "principal acceleration (PA)" quantifies the postural accelerations. Before this differentiation could be calculated, the PCA scores $c_j(t_i)$ had to be low-pass filtered with cut off frequency 5Hz.

In order to compare the postural movements between different conditions, average amplitudes of the PMs, PVs and PAs were calculated. Since the mean of the PMs, PVs, and PAs is by definition zero, and average amplitude could be calculated as the standard deviation of the coefficient over the whole duration of the trial. The standard deviation was calculated separately for each subject, for each condition and for all of the first 15 PMs. The same step was also applied to the principal velocity and principal acceleration to obtain the average velocity and acceleration amplitudes. To compare different conditions graphically, box plots were created visualizing the distribution of the amplitudes among the participants of the current study.

In addition to the PM, PV, and PA-amplitudes, center of pressure (CoP) based variables that are traditionally used in postural control research were calculated: Root mean square in A/P and M/L directions, Velocity in A/P and M/L directions, CoP area, and length of CoP trajectory.

2.7 Statistics

Dual tasking effects on the postural control variables were investigated using 1-way repeated measures ANOVAS and appropriate post-hoc tests (Bonferroni). The threshold of statistical significance was set to .05.
The dual tasking effects on the CoP variables were investigated using A multivariate 2-way repeated measures ANOVA on Stance (2) by Task (4) was conducted on all CoP variables and appropriate post-hoc tests (Bonferroni). The threshold of statistical significance was set to .05. The threshold of a trend was set to .08. If the assumption of sphericity was violated, the Huyn-Feldt results were used instead.

3 Results

The following sections contain the PCA results in both stances, quite stance and close feet, and the CoP displacement results.

3.1 PCA for Quite Stance

3.1.1 Characterization of the main Principal Movements

The first 15 PMs together quantified 98.8% of the entire body movements in QS. Tables 1 below presents the first 15 PMs with their eigenvalues and qualitative descriptions for QS.

Table 1. Eigenvalues EV_j and description of the movements for the first 15 Principal Movements in Quiet standing.

Principal Movement	Eigenvalue EV_j in %	Characterization
PM1	67.8	Ankle strategy (anterior-posterior direction)
PM2	15.0	Ankle strategy (medio-lateral direction)
PM3	6.1	Hip strategy (anterior-posterior direction)
PM4	2.4	Breathing motion in shoulders
PM5	2.1	Pelvis rotation around the vertical axis with compensatory shoulder movements
PM6	1.3	Hip strategy (medio-lateral direction)
PM7	1.0	Head nodding
PM8	0.8	Knee movement extension and flexion with hip medio-lateral movements
PM9	0.7	Multi-segment movement of the hips, shoulders and knees
PM10	0.4	Head rotation with shoulder rotation due to head movement
PM11	0.3	Chest breathing
PM12	0.3	Breathing motion visible in medio-lateral direction
PM13	0.2	Multi-segment movement of the hips, shoulders and knees
PM14	0.2	Multi-segment movement of the hips and shoulders
PM15	0.2	Multi-segment movement of the hips and shoulders

The characterization of the PMs in Quite Stance can be divided in 4 categories: movements that are associated with postural control [PMs 1-3, 5-6 and 8], movements associated with breathing [PMs 4 and 11-12], movements associated with head movements [PMs 7 and 10], and multi-segment movements that could not be clearly associated with one of the other categories [PMs 9 and 13-15].

The first 2 PMs represent sway motions around the ankle joint in anterior-posterior and in medio-lateral direction, respectively. Hip movements in A/P direction and in M/L are represented in PM3 and PM6, respectively.

PM4, PM11 and PM12 represent different movement components that were associated with breathing, indicated by a rise of shoulders in PM4 (figure 3), a rise of the sternum marker in PM11, and rise of the arms in lateral direction and flexion in the thoracic spine indicating exhale movements in PM12. See Figure 3 for an illustration of PM4.

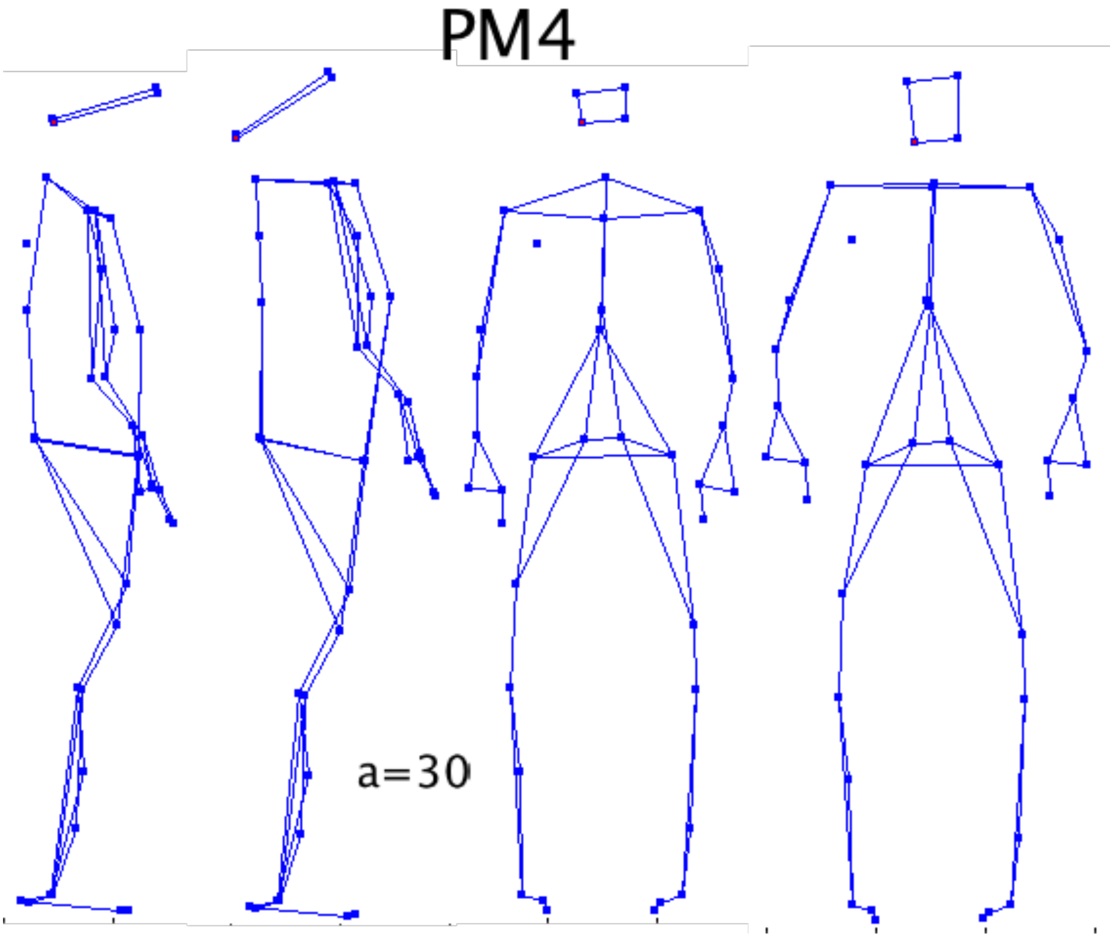

Figure 3. The fourth Principal Movement (breathing) in the sagittal plane (left panels) and frontal plane (right panels) for an exemplary participant at two time frames, amplified with 30, in Quite Stance. The rise of the shoulder belt and the volume change in the upper body is clearly visible.

PM5 represented pelvis rotation around the vertical axis, while PM7 represented head nodding. PM8 represented knee movements in the anterior-posterior direction, which are identified as knee flexion and extension movements, with compensatory movements in the hip in the medio-lateral direction.

PM9 and PMs 13-15 were associated with multi-segment movements that could not be clearly associated with one of the other categories.

The following Tables 2 and 3 provide an overview of the results of the 1-way ANOVAs on Task (4) and the pairwise comparisons (with Bonferroni corrections for multiple comparisons). Details of these findings will be described in more detail further below.

Table 2. Results from 1-way ANOVAs on condition with F-values (degrees of freedom) and p - values for the first 15 Principal Movements, Velocities and Accelerations in Quite Stance. Significant differences between the conditions are indicated in Bold.

	Movement		Velocity		Acceleration	
	F(3,30)	p	F(3,30)	p	F(3,30)	p
PM1	2.35	.092	0.96	.425	***3.62***	***.024***
PM2	0.99	.407	***4.35***	***.012***	***4.65***	***.009***
PM3	0.92	.440	***4.969***	***.006***	***6.47***	***.002***
PM4	***14.26***	***.000***	***12.83***	***.000***	***17.99***	***.000***
PM5	0.53	.665	1.44	.249	2.01	.134
PM6	0.20 *	.818	***3.65***	***.023***	***5.46***	***.004***
PM7	2.26	.102	***15.97***	***.000***	***16.47***	***.000***
PM8	1.30 *	.29	***7.86***	***.001***	***8.64***	***.000***
PM9	0.43 *	.693	***5.62***	***.004***	***6.10***	***.002***
PM10	0.98	.417	2.98 *	.057	2.60*	.086
PM11	***3.12***	***.040***	***8.63***	***.000***	***10.92***	***.000***
PM12	***7.75***	***.001***	***7.69***	***.001***	***10.92***	***.000***
PM13	1.72	.184	***4.14***	***.014***	***3.87***	***.019***
PM14	2.23 *	.105	***13.27***	***.000***	***18.67***	***.000***
PM15	***4.01***	***.016***	***9.21***	***.000***	***12.80***	***.000***

* Indicates that the assumption of sphericity was violated, and Huyn-Feldt results were used instead.

Table 3. P - values for pair-wise post hoc comparisons, corrected for multiple comparisons, for those Principal Movements, Velocities and Accelerations where significant differences were observed between the tasks in Quit Stance. There were no significant differences observed between the counting task 1 and 3.

	ST/Count 1	ST/Count 3	ST/Count 7	C1/C7	C3/C7
PM4	.009	.001			
PM11		.006			
PM12		.002			
PM15		.003			
PV2	.	.026			
PV3	.004	.028	.		
PV4	.005	.000	.023		
PV7	.003	.001	.000		
PV8	.025	.010			
PV11	.009	.021	.019		
PV12	.017	.002			
PV13		.020			
PV14	.002	.001		.018	
PV15	.007	.007			
PA1		.031			
PA2	.045	.021			
PA3	.002	.019			
PA4	.001	.001	.000		
PA7	.001	.001	.000		
PA8	.030	.046		.039	.049
PA11	.003	.015	.025		
PA12	.011	.001	.034		
PA14	.001	.001		.003	
PA15	.002	.008			

3.1.2 Postural movements in Quite Stance in single and dual tasks

This section describes differences between dual tasking conditions (single task and counting backwards) in the postural movements, i.e., PMs 1-3, 5-6 and 8. Differences in the mean amplitude in PM, PV, and PA of some movements is presented and analysed using boxplots (see Figure 4). An overview of all boxplots can be found in the appendix I (page 41).

In ankle strategy A/P (PM1), there was no significant difference between the conditions in movement and velocity amplitudes, in spite of the decreased amplitude in movement, (both ps > .092). In principal acceleration there was a significant difference in means between conditions (p .024). Post-hoc comparisons indicated that there was significantly increased amplitude in count 3 compared to single task baseline (p .031).

There were significant differences between the tasks in ankle strategy M/L (PM2) in velocity and acceleration amplitudes (both ps < .012), but no difference in movement amplitudes (p .407). In the multiple comparisons test there was a significant difference in acceleration count 1 and to count 3 (both ps< .045) compared to single task baseline. In velocity, there was e significant increase amplitude in count 3, compared to single task (p .026).

In PM3 (figure 4 for boxplot), hip strategy A/P, a significant difference between tasks was found for velocity and acceleration (both ps < .006), but no difference in movement (p .440). The multi comparison test reveals that there are significant increased amplitudes in count 1 and count 3 in velocity and acceleration, compared to single task baseline (both ps < .028).

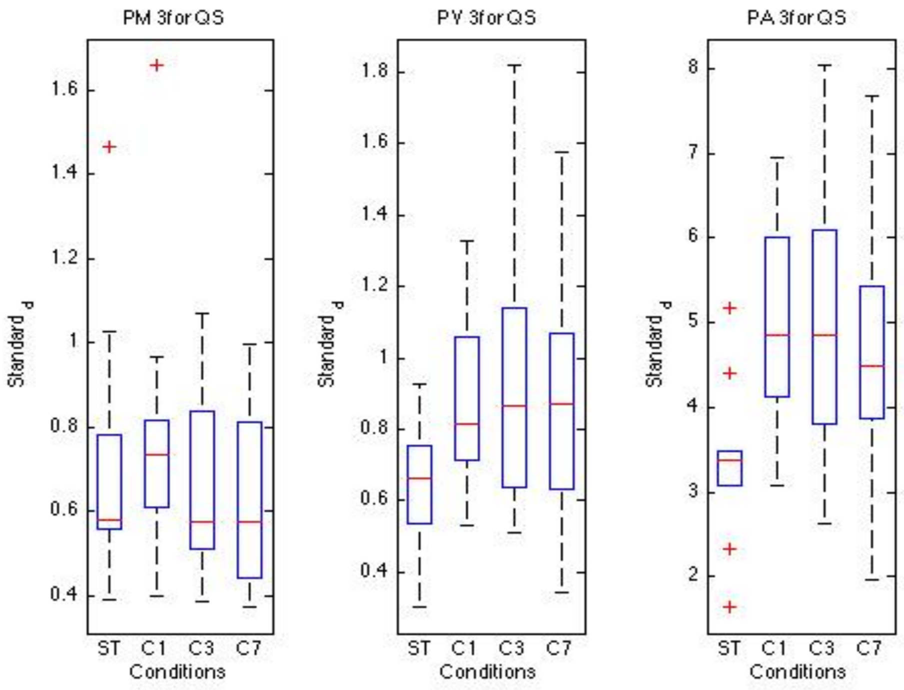

Figure 4. Boxplot of differences in the mean amplitude in PM, PV, and PA in PM3 (Hip movement A/P direction.

There were no significant differences in postural amplitude, velocity or acceleration of PM 5, pelvis rotation around vertical axis (all ps >.134).

For the hip strategy M/L (PM6) there was an increase in amplitudes in velocity and acceleration from single task to the counting tasks, and the difference between the tasks was significant (both ps < .023). However, none of the Bonferroni-corrected multiple comparisons reached the level of statistical significance.

In PM 8 (knee movement extension), there was a significant effect of task on velocity and acceleration (both ps < .001). This was confirmed in the post hoc comparisons where velocity and acceleration were significantly larger in count 1 and 3 compared to the single task baseline (both ps < .046). For acceleration, there was also a significant increase from count 1 to count 3, and from count 3 to count 7 (both ps < .049).

3.1.3 Breathing movements in Quite Stance in single and dual tasks

Three principle movements were associated with breathing movements, i.e., PMs 4 (see figure 5 for boxplot), 11 and 12. In all three PMs, there was a significant effect between the conditions of Task on amplitudes of movement, velocity and acceleration (all ps < .04). Post hoc comparisons indicated that there were increased amplitudes in PM4, movement, in count 1 and 3 compared to baseline (both ps < .009). In velocity and acceleration there were significant differences in all counting conditions compared to baseline (all ps < .023). In movement, PM11 were significant increased amplitudes in count 3 (p .006), velocity and acceleration in all counting compared to baseline (all ps < .025). In PM12 movement, significant differences were observed increased amplitude in count 3 (p .002), in the velocity between count 1 and 3 compared to baseline (both ps < .017) and in the acceleration between all counting conditions compared to baseline (all ps < .034).

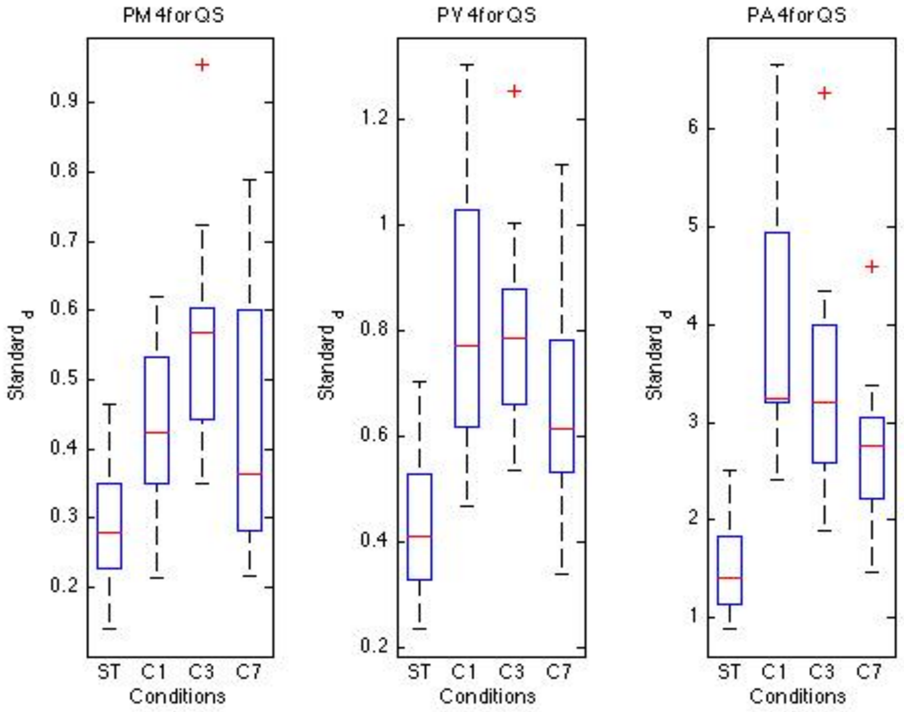

Figure 5. Boxplot of differences in the mean amplitude in PM, PV, and PA in PM4 (Breathing motion in shoulders)

3.1.4 Head movements in Quite Stance in single and dual tasks

Principled movements 7 (see figure 7 for boxplot) and 10 were associated with head movements. For head nodding (PM7), there was a significant difference observed in velocity and acceleration amplitudes between the conditions (both ps < .0005). The post hoc comparisons showed that velocity and acceleration amplitudes were significantly higher in all counting conditions compared to the single task baseline (all ps < .003).

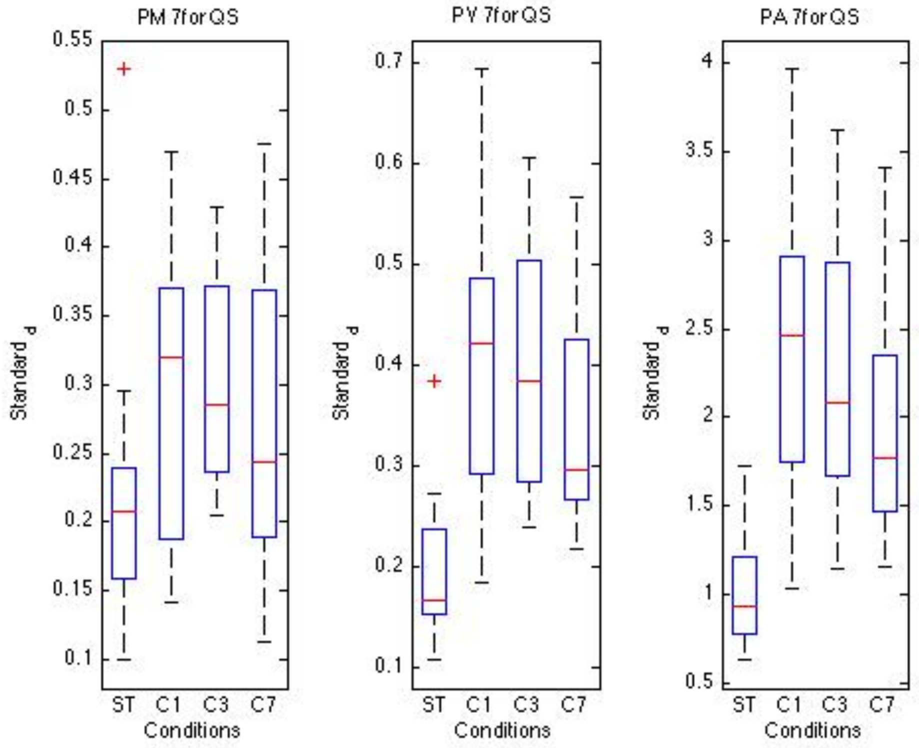

Figure 6. Boxplot of differences in the mean amplitude in PM, PV and PA in PM7 (head nodding).

For PM10 (head rotation in vertical axis and compensatory shoulder rotation), there was no significant main effect of task on amplitude of movement, velocity, or acceleration.

3.1.5 Multi segment movements in Quite Stance in single and dual tasks

PM9, 13, 14 (see figure 7 for boxplot) and 15, all showed significant main effects of Task on the mean amplitudes of velocity and acceleration. In addition, there was a main effect of Task on movement amplitude in PM15. However, in PM15 no difference is seen in the multi comparisons test. In PM 13-15 the ANOVA reveals significant results in velocity and acceleration (all ps < .019) and movement in PM15 shows significant difference (ps .014). In the multi comparison test, there is significant increased amplitudes in count 3 (ps .020) in PM13, compared to single task baseline. There is no difference in movement and acceleration. In PM14 and 15 there is significant increased amplitudes in count 1 and count 3 (all ps < .008) in velocity and acceleration, compared to single task baseline. PM 15 reveals also significant increased amplitude in movement in count 3 compared to baseline (ps .003).

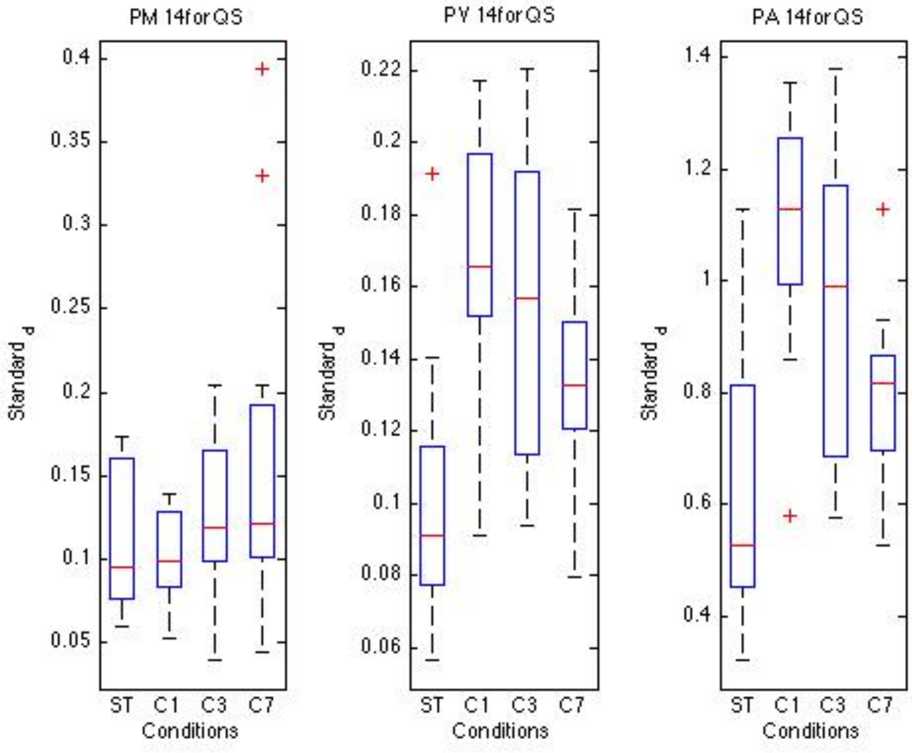

Figure 7. Boxplot of differences in the mean amplitude in PM, PV and PA in PM14 (multi-segment movement in hip and knees).

3.2 PCA for Close Feet

3.2.1 Characterization of the main Principal Movements

The first 15 PMs together quantified 98.6% of the entire body movement in close feet. Table 4 below presents the first 15 PMs with their eigenvalues and qualitative descriptions for CF.

Table 4: Eigenvalues EV_j and description of what movement the first 15 Principal Movements characterize in Close feet.

Principal Movement	Eigenvalue EV_j in %	Characterization
PM1	48.0	Ankle strategy (anterior-posterior direction)
PM2	38.0	Ankle strategy (medio-lateral direction)
PM3	3.4	Hip strategy (anterior-posterior direction)
PM4	2.5	Breathing motion in shoulders
PM5	1.5	Pelvis rotation around the vertical axis with compensatory shoulder and head movements
PM6	1.3	Head Nodding
PM7	1.0	Hip strategy (medio-lateral direction)
PM8	0.8	Knee extension and flexion
PM9	0.6	Head movement and shoulder rotation due to head movement
PM10	0.4	Head rotation and shoulder rotation due to head movement
PM11	0.3	Multi-segment movement of the hips, shoulders and knees
PM12	0.2	Multi-segment movement of the hips, shoulders and knees
PM13	0.2	Chest breathing
PM14	0.2	Multi-segment movement of the hips, shoulders, knees and head
PM15	0.2	Breathing motion visible in medio-lateral direction

As can be seen in Table 4, the first 7 PMs each quantified more than 1% of the variability and together they quantified 95.7% of the entire body movement. From PM 8, the eigenvalues drop below 1%. In CF, the ankle sway in M/L directions became more important (38%) compared to quite stance with feet at hip-width stance (15.0%, see Table 1). The first two PMs (ankle sway) represented 82.8% of the entire body movement in QS and 86% in CF. the relative contribution of hip movements in

A/P direction were almost double in QS (6.1%) compared to CF (3.4%). The remainder of the PMs in both stances had approximately the same percentages.

As for QS, the first 2 PMs represented sway movements around the ankle joint in anterior-posterior and in medio-lateral directions. Hip movements in A/P and in M/L directions were represented in PM3 and PM7.
PM4, PM13 and PM15 represented different movement components that were associated with breathing, indicated by a rise of shoulders in PM4, a rise of the sternum marker in PM13 and rise of the arms in lateral direction in PM15.
PM5 represented pelvis rotation around the vertical axis, and head nodding in PM 6.
PM8 represented knee movements in the anterior-posterior direction, which were identified as knee flexion and extension movements. PMs 9-10 were associated with head rotation and compensatory movements in shoulders and shoulder rotation. PMs 11-12 and PM14 represented multi-segment movements of shoulders, hips and knees.

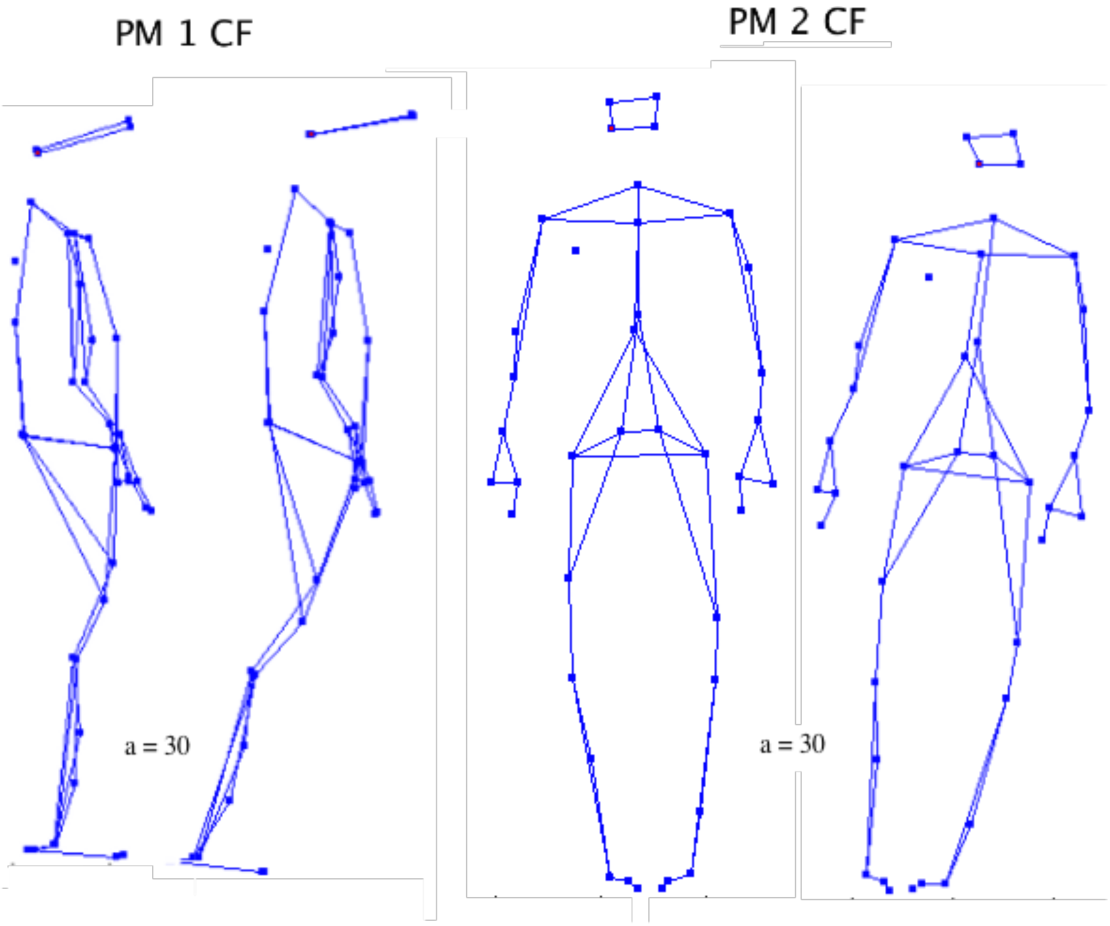

Figure 8. Left panels: The first Principal Movement in the sagittal plane for an exemplary participant at two time frames, amplified with 30, in Close Feet. Right panels: The second Principal Movement in the frontal plane for an exemplary participant at two time frames, amplified with 30, in Close Feet.

Several changes in the relative importance of the different PMs occurred when standing with feet close together, but the 4 categories remained the same: movements that are associated with postural control [PMs 1-3, 5 and 7-8], movements associated with breathing [PMs 4, 13 and 15], movements associated with head movements [PMs 6 and 9-10] and multi-segment movements that could not be clearly associated with one of the other categories [PMs 11-12 and 14].

As for QS, the standard deviation was calculated separately for each subject, for each condition and for all of the first 15 PMs. The same step was also applied to the principal velocity and principal acceleration to obtain the average velocity and acceleration amplitudes.

The following Tables 5 and 6 provide an overview of the 1-way repeated measures ANOVA on Task (4) and the post hoc comparisons with Bonferroni corrections, respectively.

Table 5. Results from 1-way ANOVAs on condition with F-values (degrees of freedom) and p - values for the first 15 Principal Movements, Velocities and Accelerations in Close Feet. Significant differences between the conditions are indicated in Bold.

	Movement		Velocity		Acceleration	
	F(3,30)	p =	F(3,30)	p =	F(3,30)	p =
PM1	1.57	.216	2.95 *	.093	3.02 *	.082
PM2	2.98	.416	1.51	.248	2.80	.057
PM3	1.23	.316	***9.39***	***.000***	***11.48***	***.000***
PM4	***9.11 ****	***.002***	***67.39***	***.000***	***57.25***	***.000***
PM5	2.48	.080	***6.04***	***.002***	***5.94***	***.003***
PM6	2.60 *	.097	***11.45***	***.000***	***10.09***	***.000***
PM7	2.08	.123	***4.63***	***.009***	***6.88***	***.001***
PM8	1.24	.311	***9.96 ****	***.001***	***12.47 ****	***.001***
PM9	***5.00***	***.006***	***7.62 ****	***.005***	***10.67 ****	***.001***
PM10	***5.37***	***.004***	***9.25***	***.000***	***10.18***	***.000***
PM11	0.78	.514	***9.57***	***.000***	***9.74***	***.000***
PM12	2.34	.093	***5.01 ****	***.029***	***4.76 ****	***.036***
PM13	2.17	.112	***21.64***	***.000***	***20.00***	***.000***
PM14	***5.36***	***.004***	***11.57***	***.000***	***10.26***	***.000***
PM15	2.38	.089	***6.78***	***.001***	***6.96***	***.001***

* Indicates that the assumption of sphericity was violated, and Huyn-Feldt results were used instead.

Table 6. P - values of those Principal Movements, Velocities and Accelerations where significant differences were observed in the post hoc multiple comparisons test in Close feet. There were no significant differences observed between the counting tasks.

	ST/count 1	ST/count 3	ST/count 7
PM4	.001	.013	.024
PM9		.027	
PM10	.012		
PM14		.016	.030
PV3	.001	.039	.009
PV4	.000	.000	.000
PV5	.022		
PV6	.001	.006	.013
PV7	.037		.047
PV8	.007	.029	.002
PV9	.001		.001
PV10	.001	.032	.023
PV11	.007	.021	.005
PV13	.004	.000	.001
PV14	.001	.002	.005
PV15		.017	
PA3	.002	.027	.003
PA4	.000	.000	.000
PA5	.019		
PA6	.001	.017	.016
PA7	.002		.036
PA8	.003	.030	.001
PA9	.000	.030	.001
PA10	.001	.036	
PA11	.005	.039	.004
PA13	.004	.001	.001
PA14	.004	.003	.008
PA15	.022	.013	

3.2.2 Postural movements in Close Feet in single and dual tasks

This section describes differences between dual tasking conditions (single task and counting backwards) in the postural movements, i.e., PMs 1-3, 5 and 7-8. Differences in the mean amplitude in PM, PV, and PA of some movements is presented and analysed using boxplots. An overview of all boxplots can be found in the appendix II (page 46).

For the first two ankle strategies in A/P and M/L (PM 1-2) there was no significant main effect difference in movement, velocity and acceleration between the mean amplitudes, in all conditions.

The hip strategy A/P (PM3, see figure 9 for boxplot) main effect showed significantly increased amplitudes in velocity and acceleration (both ps < .0005). The multi comparisons test confirmed that there was increased amplitudes, which is significant different in all counting conditions compared to the single task baseline in velocity and acceleration (all ps < .039). There was no significant result in ANOVA and multi comparisons test for movement in PM3.

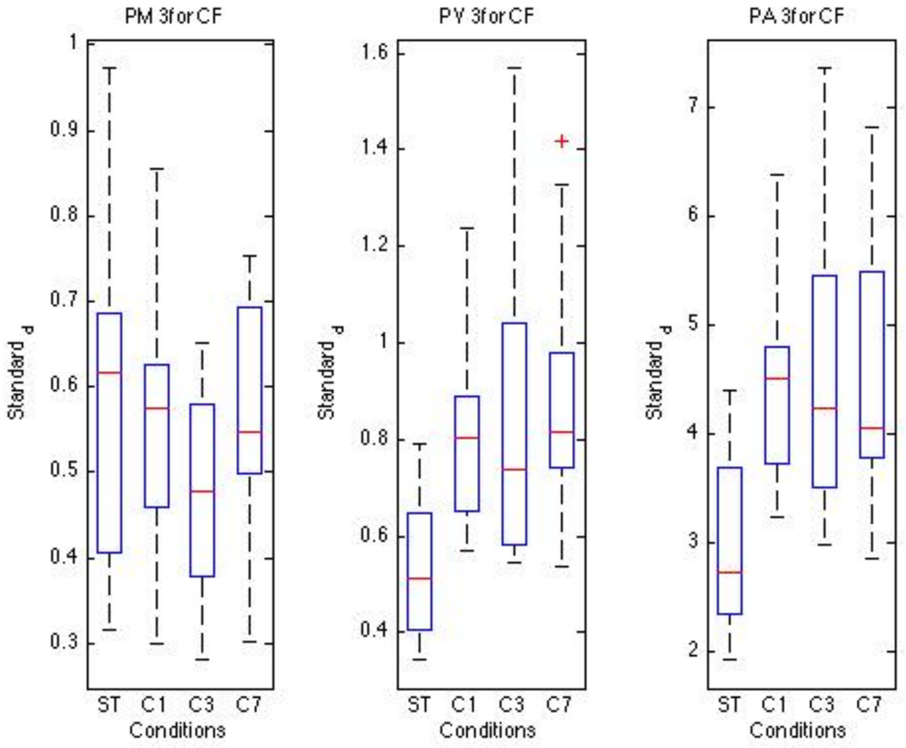

Figure 9. Boxplot of differences in the mean amplitude in PM, PV and PA in PM3 (hip movement in A/P direction).

In PM5 (hip rotation and compensatory shoulder and head movements) there was a main effect with a significant increase in amplitudes in velocity and acceleration (both ps < .003). The multi comparisons test showed significant increased amplitudes in count 1, compared to single task baseline in both velocity and acceleration (both ps < .022). There were non-significant results in movement.

For the other hip strategy M/L (PM7) increased amplitudes in velocity and acceleration gives a significant difference between the means (both ps< .009). The significant increased amplitudes were less in velocity in count 1 and 7 compared to baseline (both ps < .047) than the increased amplitudes in acceleration in count 1 (p= .002) and 7 (p .036) compared to baseline, as indicated in multi comparisons test (table 6).

There were also increased amplitudes in velocity and acceleration in PM8 (knee extension) that showed significant main effects results (both ps .001). The multi comparisons test in velocity and acceleration, showed that there was a lower significant result in count 1 (both ps < .007) and count 7 (both ps < .002) than count 3 (both ps < .030) compared to single task baseline.

3.2.3 Breathing movements in Close Feet in single and dual tasks

For the breathing movements in PM4 (breathing motion in shoulders), PM13 (chest breathing, see figure 10 for boxplot), and PM15 (breathing motion visible in medio-lateral direction) showed increased amplitudes in all attributes, such as movement, velocity and acceleration. The main effect of PM4 showed significant difference between all attributes (all ps < .002). PM13 and 15 shows significant difference between the conditions in velocity and acceleration (all ps < .001). The post hoc multi comparisons test showed that there was significant difference in all counting conditions compared to single task baseline in movement (all ps < .024) in PM4. Also velocity and acceleration in PM4 showed significant difference in all counting compared to single task baseline (all ps < .0005). However, no significant results in PM13 and 15 in movement. PM15 in velocity was significant increased amplitude difference in count 3 (ps .017) and accelerations in count 1 and count 3 compared to baseline (ps < .022).

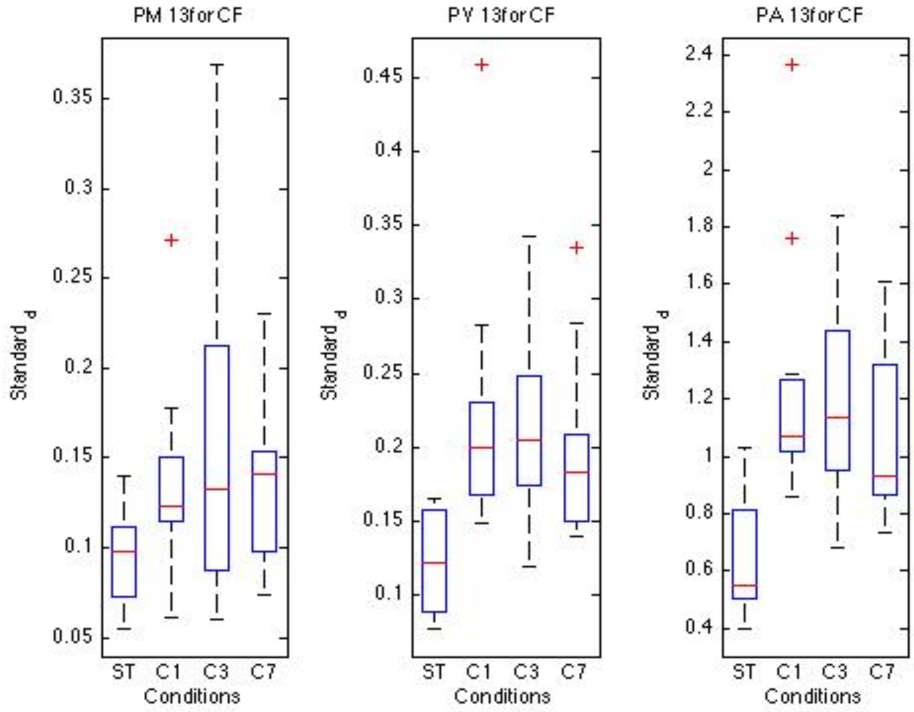

Figure 10. Boxplot of differences in the mean amplitude in PM, PV and PA in PM13 (chest breathing).

3.2.4 Head movements in Close Feet in single and dual tasks

For the head nodding (PM6) there was a significant difference between the means in velocity and acceleration (both ps .000). Multi comparisons test shows that comparing baseline to all counting condition there was significant increased amplitude in all of the counting conditions (all ps < .017). There were no significant differences in movement.

In head rotation in vertical axis with compensatory shoulder rotation in PM9-10 (see figure 10 for boxplot), there was a main effect in all, movement, velocity and acceleration (all ps < .006). Multi comparisons test reveal that velocity in PM9 was significant in count 1 and count 7 compared to single task baseline (both ps .001), acceleration was also significant in these two conditions (both ps < .001) and in count 3 (p .030) compared to single task baseline. In movement PM9 was significant in count 3 (p .027) and count 1 (p .012) in PM10, compared to the baseline. Velocity in PM10 was significant different with increased amplitudes in all counting conditions (all ps < .032) and acceleration in count 1 and 3 (both ps < .036) compared to baseline.

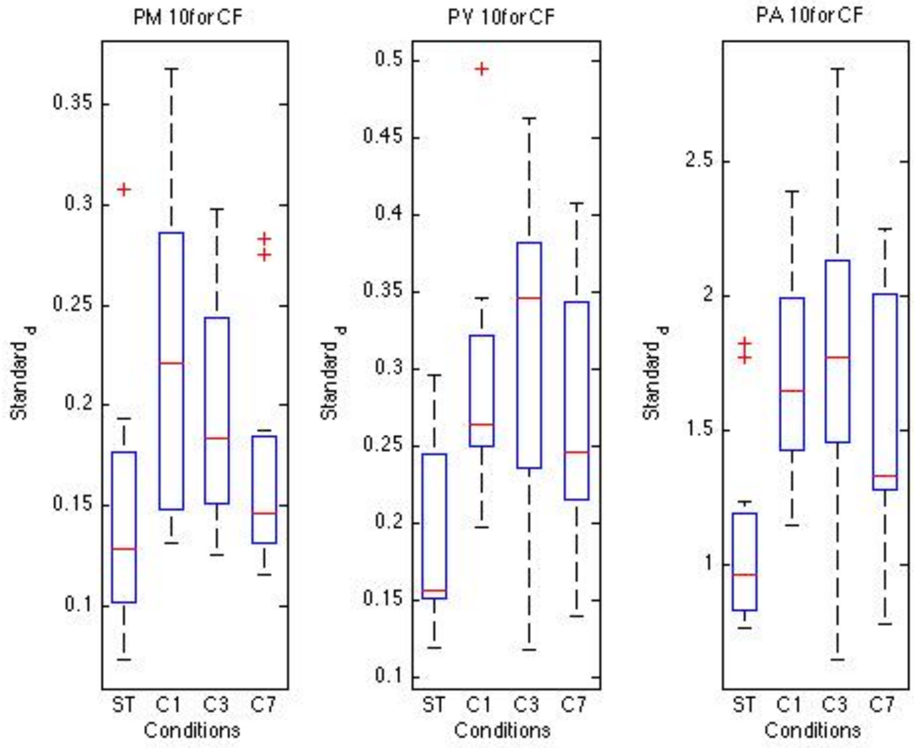

Figure 10. Boxplot of differences in the mean amplitude in PM, PV and PA in PM10 (head rotation and shoulder movements).

3.2.5 Multi segment movements in Close Feet in single and dual tasks

In multi segments movement in PM11 was significant increased amplitude in velocity and acceleration (both ps .000). PM12 showed exactly the same, with less increased amplitudes (both ps < .036). PM14 (see figure 11 for boxplot) showed increased significant difference in all attributes, movement, velocity and acceleration (all ps < .004).

In the multi comparison test there was no significant results in movements for PM11 and 12. PM14 showed significant results with increased amplitudes count 1 (ps .014) and count 3 (ps .030) in movement compared to single task baseline. Velocity and acceleration in PM11 showed there was significant increased amplitudes in all counting conditions compared to baseline, where count 1 and 7 eas higher significant (all ps < .007) than count 3 (both ps < .039). PM12 have no significant results to show in both velocity and acceleration. There were significant increased amplitudes in all counting conditions in PM 14 compared to single task baseline (all ps < .008).

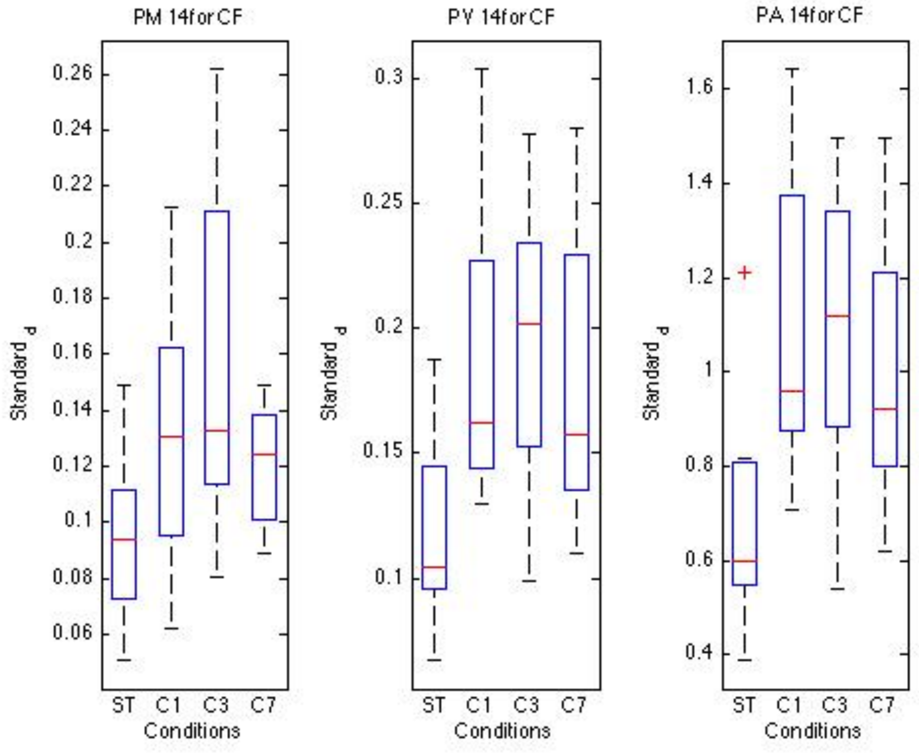

Figure 11. Boxplot of differences in the mean amplitude in PM, PV and PA in PM14 (multi-segment movements in head, shoulders and knees).

3.3 Center of pressure

The following tables provide an overview of multivariate 2-way repeated measures ANOVA on Task (4) and stances (2) and the post hoc comparisons with Bonferroni corrections, respectively.

Table 7: F - and p – values for the multivariate, 2-way repeated measures ANOVA Stance (QS and CF) by Task (Single, C1, C3, C7) on RMS A/P, RMS M/L, Velocity A/P, Velocity M/L, Area and Trajectory of the Center of Pressure displacement.

Source	**Measure**	**F(1,8)**	**p**
Stance	RMSap	.438	.527
	RMSml	***9.584***	***.015***
	Velocity A/P	***7.999***	***.022***
	Velocity M/L	***25.634***	***.001***
	Area	***45.144***	***.000***
	Trajectory	***8.838***	***.018***
Source	**Measure**	**F (3,24)**	**p**
Task	RMSap	1.395	.268
	RMSml	1.365	.277
	Velocity A/P	2.537	.081
	Velocity M/L	1.962*	.147*
	Area	2.863	.058
	Trajectory	***7.218***	***.001***
Source	**Measure**	**F (3,24)**	**p**
Stance*Task	RMSap	.678	.574
	RMSml	.374*	.692
	Velocity A/P	1.363	.278
	Velocity M/L	.123	.946
	Area	.312*	.697*
	Trajectory	.321	.810

* Indicates that the assumption of sphericity was violated, and Huyn-Feldt results were used instead.

Stance had a significant main effect on all variables except RMS A/P (all ps< .022). Task had a main effect on Trajectory only (p < .001), and a trend on Area (p= .058). Post hoc comparisons indicated that trajectory were significant difference between count 1, compared to baseline (p .039). There were no significant interactions between Stance and Task (all ps > .278, see Table 7).

4 Discussion

The aim of this study was to investigate the effect of dual tasking on postural control with the following specific question: Does the type and magnitude of postural control movements depend on the difficulty of concurrent cognitive tasks, the level of difficulty of stances, or both? In a controlled laboratory setting, participants stood quietly in two different stances (feet hip-width apart or close together) during single task and while performing three different counting tasks (counting backwards in 1s, 3s, or 7s). Analyses of the center of pressure indicated that the position of the feet had a significant effect on all variables except RMS in anterior-posterior direction. Task had an effect on length of CoP trajectory only, while none of the interactions were significant. The PCA analyses identified four main types of movements: postural movements, breathing movements, head movements, and multi segment movements. The largest principal movements, PM1 and PM2 (representing ankle sway in A/P and M/L directions, respectively) differed between the two stances, with ankle sway in A/P contributing less and in M/L direction more when standing with feet close together compared to hip-width apart. There were few significant differences between the tasks in the movement amplitudes, but many in the movement velocity and acceleration. These findings will be discussed below.

4.1 CoP displacement

In the CoP measurement, there were several main effects of stance in the variables, thus only one main effect of task in the length of trajectory. There were no interactions between stances and tasks. Standing in hip-width stance is a stable and often used position. A study by Mylène C. Dault, Geurts, Mulder, and Duysens (2001) showed that a cognitive stroop test while standing with feet hip-width stance had no effect on postural sway as indicated by CoP displacement in young, healthy participants. Other studies found that young participants even decreased CoP displacement. For example, Bernard-Demanze, Dumitrescu, Jimeno, Borel, and Lacour (2009) had two levels of cognitive tasks while standing in a natural, shoulder-width stance. The young participants stabilized their posture by decreasing CoP displacement. Huxhold, Li, Schmiedek, and Lindenberger (2006) found a decrease in CoP displacement under all cognitive dual tasks, even for low demanding cognitive tasks in young participants. The authors proposed that the improvement of postural control performance might be due to directing attention away from the highly automatized postural control task and instead directing it more towards the secondary task. In this way, postural control is hypothesized to be controlled more from the sub-cranial nervous system, which could improve the efficacy of the postural control mechanism. Arousal is also mentioned as a potential factor for explaining these effects. Andersson, Hagman, Talianzadeh, Svedberg, and Larsen (2002) propose that increased arousal could cause improved postural performance in low demanding cognitive tasks, while higher demanding tasks could raise arousal too high and leading to deterioration of the performance. Although while conducting studies of the dual task interference, the researchers have no control over what participants think about during single task baseline. The cognitive task may not be an extra attentional load compared to single task baseline. Mylène C Dault et al. (2001) conducted different postural tasks, such as shoulder-width stance and tandem-stance, with three different levels of working memory tasks. They did not find changes in postural control between the different levels of working memory task, indicating that the different stances did not affect the performance of working memory tasks. However, they did find a significant effect of mental task for shoulder-width stance in RMS A/P direction and in M/L direction in tandem-stance. In tandem stance the ankle invertors/evertor joints is lined up and the width of the base of support is small which means the postural control have to stabilize more in both A/P and M/L. In shoulder-width stance, there is bigger base of support that is more controlled in A/P direction. The current study showed difference in RMS M/L between the stances, thus no changes in the cognitive task conditions. In contrast, a study by Hunter and Hoffman (2001) on the effects of a visual task while standing in tandem-stance revealed that participants sway less while performing a secondary task, than during no cognitive task. This may be due to muscle tension being higher when attention is on the secondary task. It has also been suggested that articulation of answers may be responsible for increased sway path due to increased respiration (Yardley, Gardner, Leadbetter, & Lavie, 1999). This hypothesis is supported by the results in the current study which found not only an increased CoP trajectory length during the counting tasks, but also significant changes due to dual tasking in the breathing movement components.

Although we have gained significant knowledge about effects of stance and dual tasks from force plate measurements, CoP is a rather coarse measure that summarized all postural movements but does not differentiate between the different movements.

Therefore, a PCA was also applied in the current study. These results are discussed next.

4.2 Principal component analysis

The application of the PCA separated the complex multi-segment movements of all participants into separate one-dimensional linear movement components. A previous study of Federolf et al. (2013) that used a PCA-decomposition of postural movements in different stance positions, indicated that this method is highly sensitive for detection of postural movements. For example, it was shown that both biomechanical and physiological movement patterns, such as breathing and postural movements, could be identified in the different principal movements. In previous studies (Horak & Nashner, 1986; Winter et al., 1996) that did not use PCA, ankle and hip strategies were difficult to distinguish from other multi-segment movement strategies.

4.2.1 Postural movements

The present study shows that principal movement components represent distinct movement strategies that agree well with the strategies described by Winter et al. (1996) and Horak and Nashner (1986). The ankle and hip strategies are the main movement strategies that have been described in studies with force plate measurements (Winter et al. (1996); Horak and Nashner (1986)), however, they are difficult to distinguish if only CoP data are available. The current study demonstrated that by comparing the eigenvalues, changes in the relative contributions of different postural movement strategies – e.g. when changing from QS to CF, can easily be detected.

Another interesting observation in the current study was that changes the neuromuscular processes involved in postural control – in the current study facilitated through the concurrent cognitive tasks - may not affect the amplitude of postural control strategies, but rather the velocities and accelerations that control the amplitude of movements. Furthermore, there was a clear tendency that higher order movement components were more sensitive to changes than the lower order movement components which dominate CoP movements. This relates to a recent study of Yamamoto et al. (2015) which concluded that CoP outcomes are not very informative for characterizing neural control or subject-dependent biomechanics during quite stance in healthy young persons.

4.2.2 Breathing movements

PCA was also capable of identifying different body movements associated with breathing, namely , breathing by lifting the shoulders, breathing with the stomach, and breathing by medio-lateral lifts of the arms, indicating chest breathing. Also, the PCA is sensitive to pick up differences in these movements in principal movement, principal velocity and principal acceleration as an effect of task.

Compared to the single task condition in which the participants can be assumed to be breathing normally, they inhale and exhale more when they have to say out loud the numbers while counting backwards. This change in respiratory pattern is clearly reflected in the increased amplitudes of velocity and acceleration. This supports results of Yardley et al. (1999) and Mylène C Dault, Yardley, and Frank (2003) who saw a difference in sway path length due to articulation in a mental task compared to conducting silent tasks, which did not results in differences in path sway. This effect may also be the reason for the significant increase in CoP trajectory in the current study. These authors also suggested that this could reflect central interference since speech and balance may share common structures.

4.2.3 Head and multi-segments movements

When performing a challenging counting task, many people nod their head. This was also the case in the present study, with significant effects on velocity and acceleration of amplitude in both stances, and on movement amplitude when standing with feet close togheter. The head nodding may be an involuntary (or even voluntary) behavior that supports the cognitive task, but is not necessarily linked to changes in the neuromuscular control of posture. Thus nodding or similar behavior (e.g. a rhythmic hand or arm movement) has the potential to contaminate CoP-based variables in studies that are interested in changes in the neuromuscular control of posture. In the current study no impact of nodding on CoP-based variables could be observed, nevertheless, the PCA analysis did offer a method to separate it from other postural movement components, thus offering more reliable data for the study of neuronal rather than behavioral postural control processes. The multi-segment movements are where the entire body is performing several movements of shoulders and hip. They may play an important role in postural control, which the results indicate. There are significant difference in movement, velocity and acceleration in both stances and is affected by cognitive task, compared to single task baseline. This indicates that head and multi-segment movements are involved in postural control, but CoP measures were not sensitive to pick up effects of movements in dual task.

4.2.4 Dual task interference

Postural control requires continuous regulation and integration of multiple types of sensory input by the central nervous system (CNS). Primarily three systems, the visual, vestibular and somatosensory systems, provide relevant information about the position of the body's center of gravity and movements (Hunter & Hoffman, 2001). Earlier it was thought that postural control is largely automatic. However, it has more recently been suggested that maintaining postural stability does require some degree of attention (Kerr et al., 1985). This implies that cognitive processing may influence balance because they both may rely on neural mechanisms. The inverted pendulum model suggests that the ankle stabilizes body sway, necessitating only sensory input from the ankle about the body's position. However, in multi-segment movements the CNS is involved in controlling all the joints of the body (Hsu et al., 2007). The current study shows that high multi-segment movement components are indeed involved with postural control as the results showed there were significant differences in movement, velocity and acceleration of cognitive task A previous study on standing by Rankin, Woollacott, Shumway-Cook, and Brown (2000) showed that with a secondary task, there is a reduction in the activation of the gastrocnemius muscle compared to no cognitive task. In contrast, the present study found that when conducting a concurrent cognitive task, i.e. when postural control is believed to relies more on the spinal processes (Morasso, Baratto, Capra, & Spada, 1999), the amplitude of postural velocity and postural acceleration increased significantly. Increased acceleration implies that higher forces were involved in controlling the posture. This may provide insight into the functional role of the CNS-involvement in postural control: by creating smoother movements, smaller forces are needed and facilitating reduced physiological cost. If the spinal cord is more involved in controlling posture, the amplitudes of the movement components were largely unaffected, but the acceleration amplitudes increased, suggesting that control was a less efficient and physiologically more costly.

5. Conclusion

The results of this study indicated that PCA provides additional information about body movements during postural control and concurrent cognitive tasks, compared to CoP measures. Most CoP measures, except magnitude of anterioposterior sway, were significantly affected by stance position, indicating that stance influences postural movements. Especially mediolateral sway increased when standing with feet close together. However, CoP measures were not sensitive to effects of dual tasking. In contrast, PCA showed that high order movement components, such as breathing, head movements and other multi-segment movements, are involved in postural control and in particular these movements were affected by a concurrent cognitive task. Especially the velocity and acceleration amplitude of the movements increased during dual tasking, even in relatively young, healthy participants performing simple postural and counting tasks. These results open up for future research to use the PCA method to investigate in more detail postural control in populations with different disorders, for example people with Parkinson's disease, elderly non fallers compared to elderly fallers, and other populations with difficulties in relation to balance.

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Appendix I

The boxplots (PM1-15) for Quite Stance shows the differences in the mean amplitude in PM, PV, and PA.

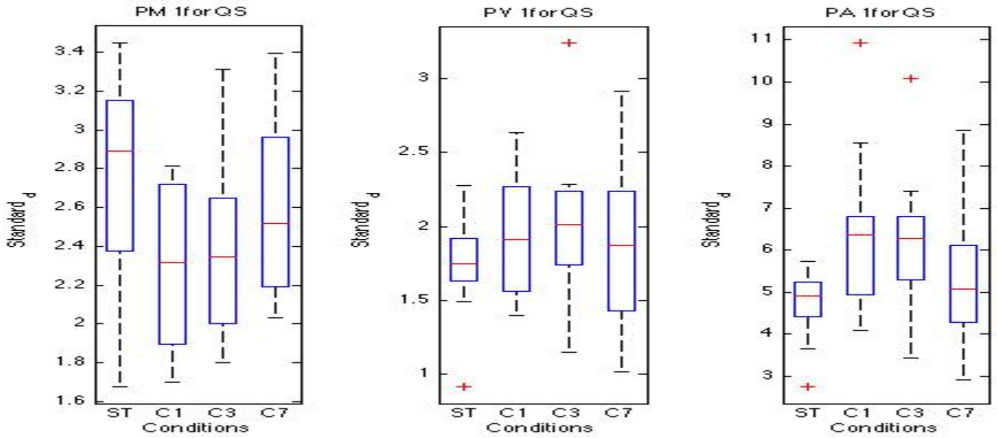

Figure 11. Boxplot for PM 1 (Ankle A/P)

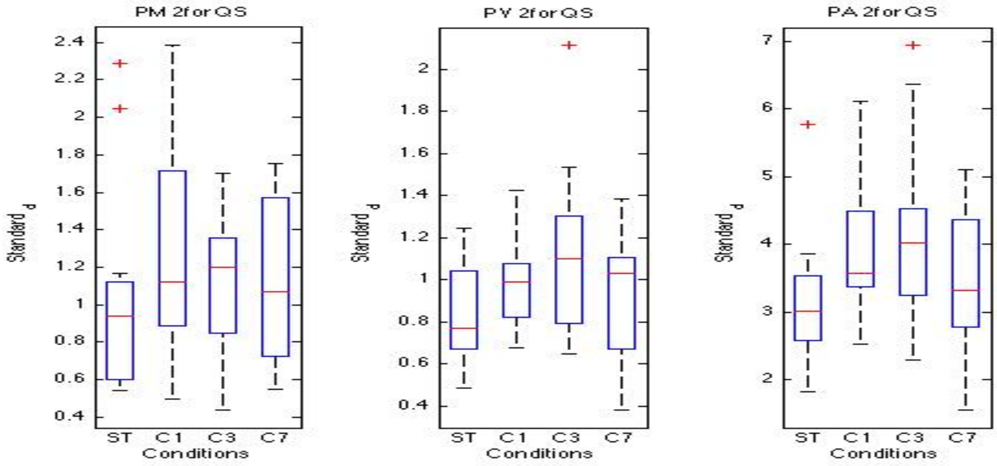

Figure 11. Boxplot for PM 2 (Ankle M/L)

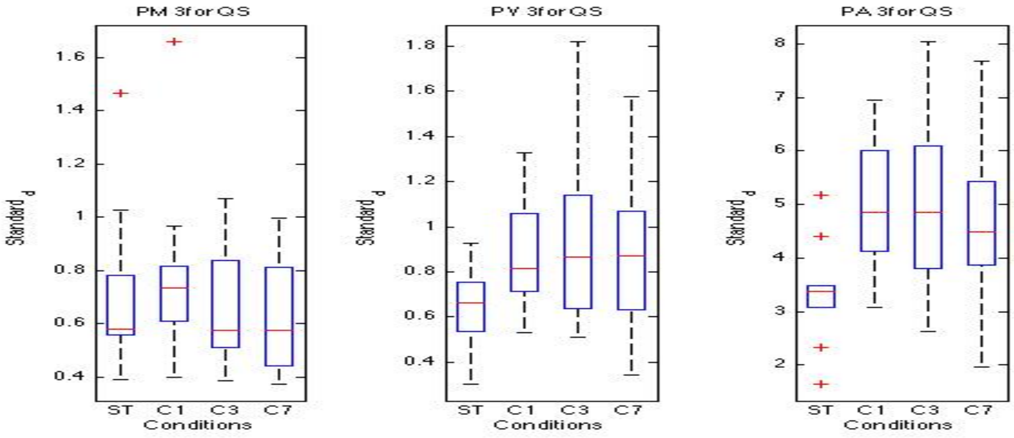

Figure 13. Boxplot for PM 3 (Hip A/P)

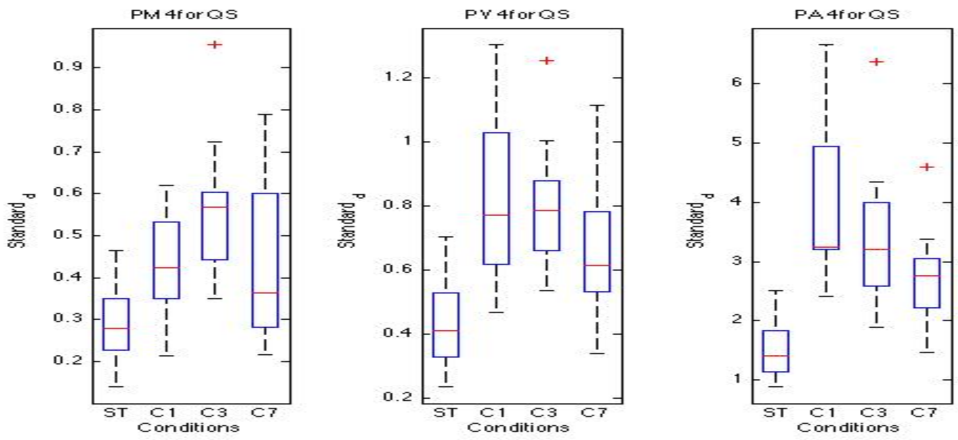

Figure 14. Boxplot for PM 4 (Breathing motion in shoulders)

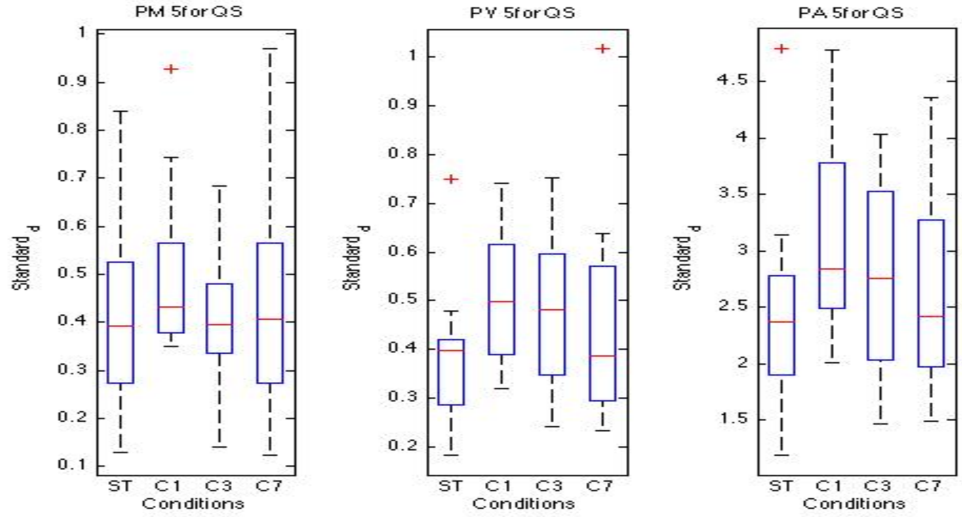

Figure 15. Boxplot for PM 5 (Pelvis rotation around the vertical axis with compensatory shoulder movements)

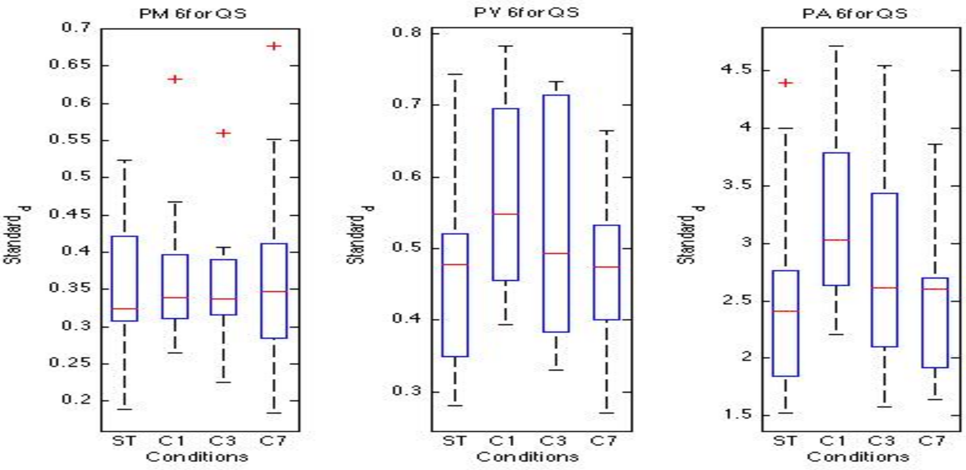

Figure 16. Boxplot for PM 6 (Hip strategy M/L)

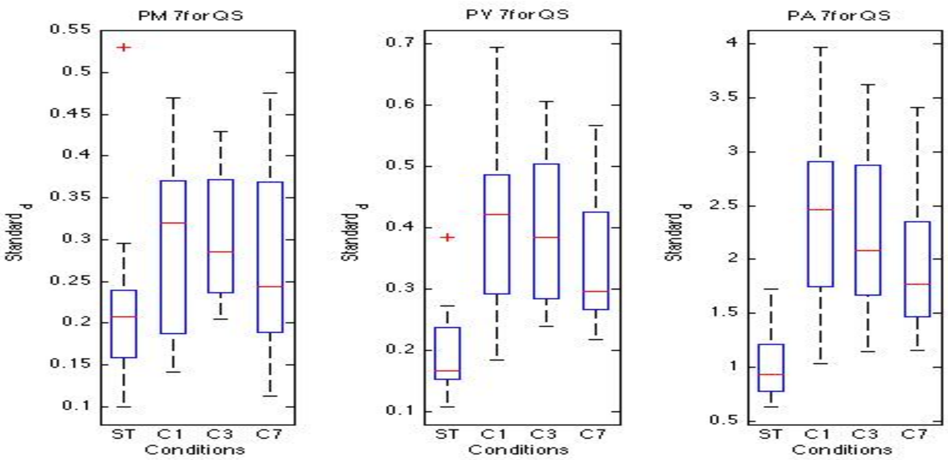

Figure 17. Boxplot for PM 7 (Head nodding)

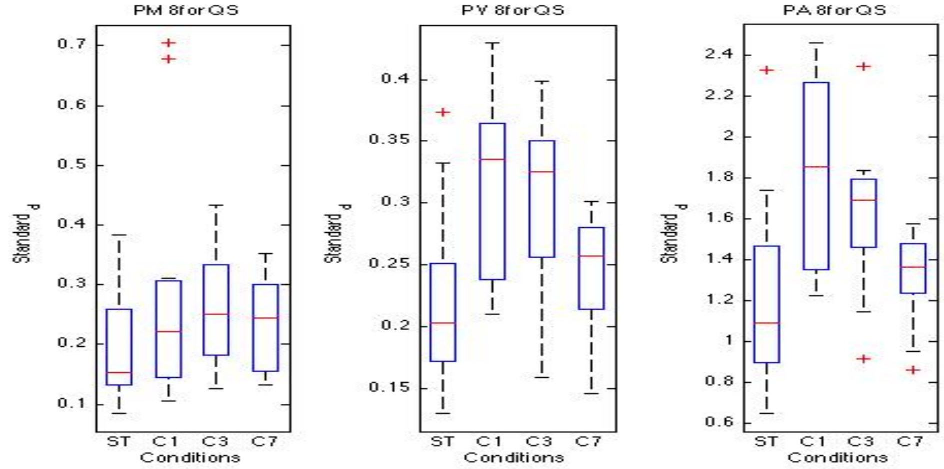

Figure 18. Boxplot for PM 8 (Knee movement extension with hip medio-lateral movements)

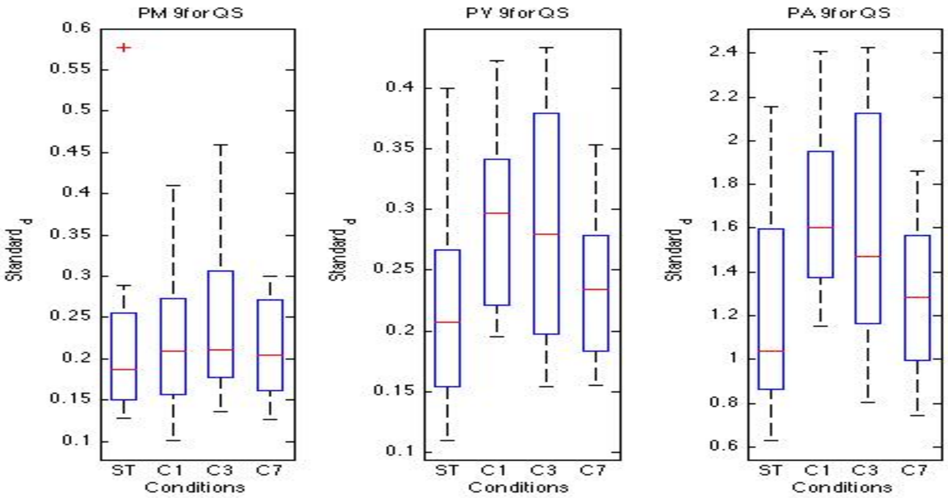

Figure 19. Boxplot for PM 9 (Multi-segment movement of the hips, knees and head)

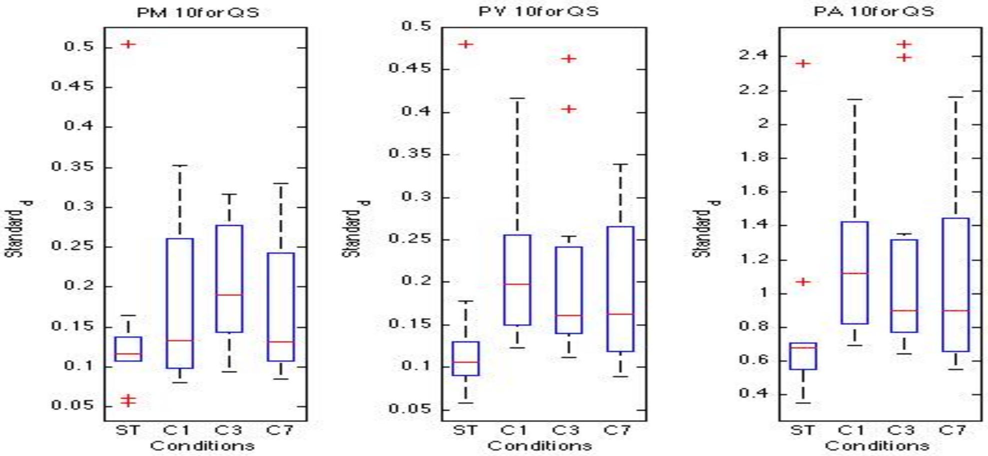

Figure 20. Boxplot for PM 10 (Head rotation with shoulder rotation due to head movement)

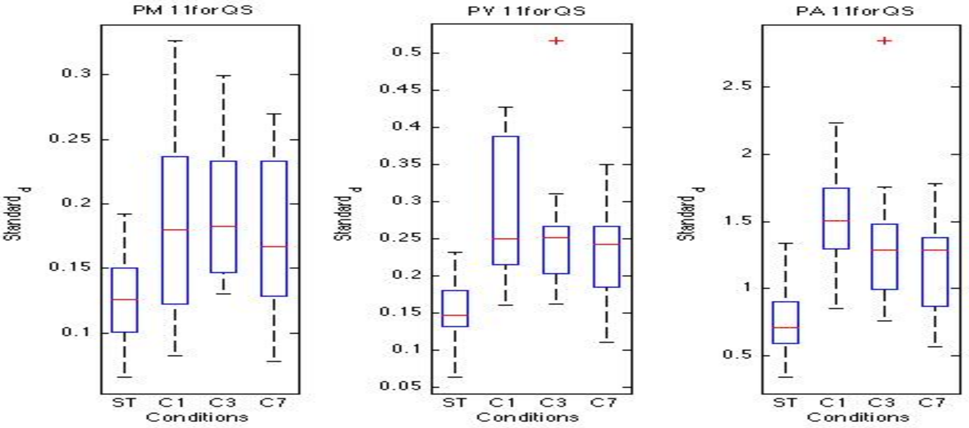

Figure 21. Boxplot for PM 11 (Chest breathing)

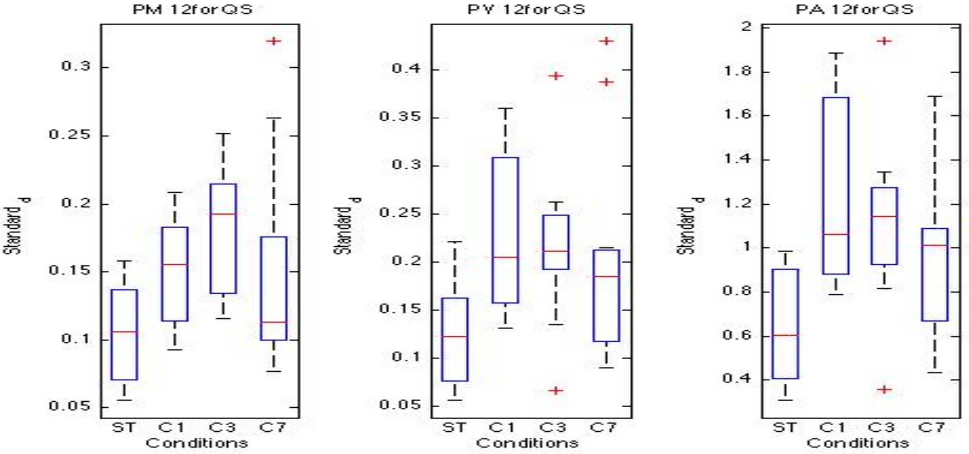

Figure 22. Boxplot for PM 12 (Breathing visible in medio-lateral direction)

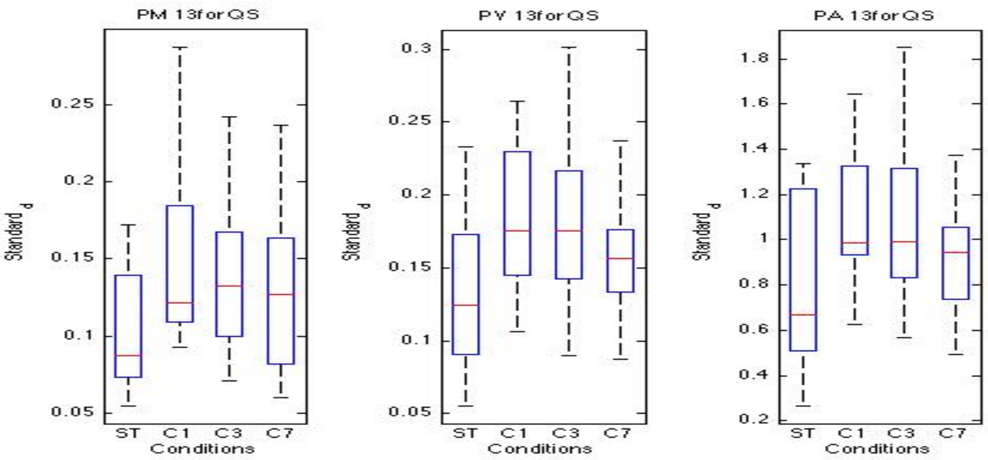

Figure 23. Boxplot for PM 13 (Multi-segment movement of the hips, knees and head)

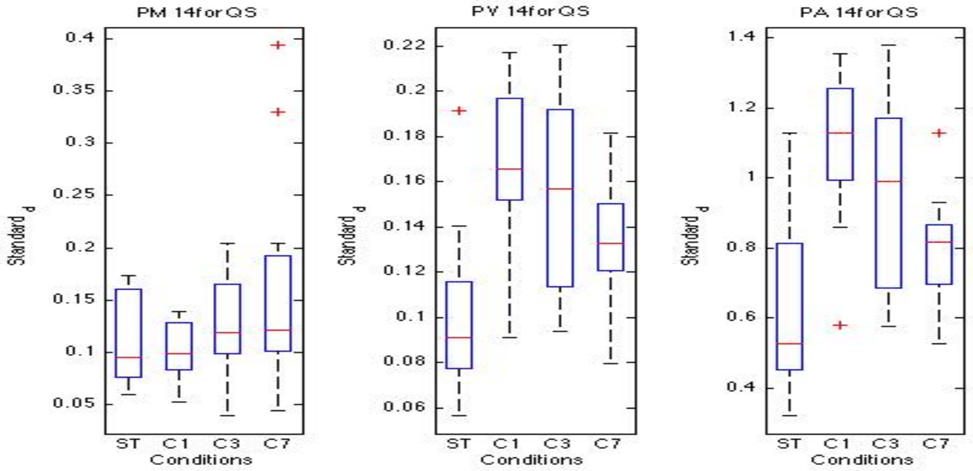

Figure 24. Boxplot for PM 14 (Multi-segment movement of the hips, knees and head)

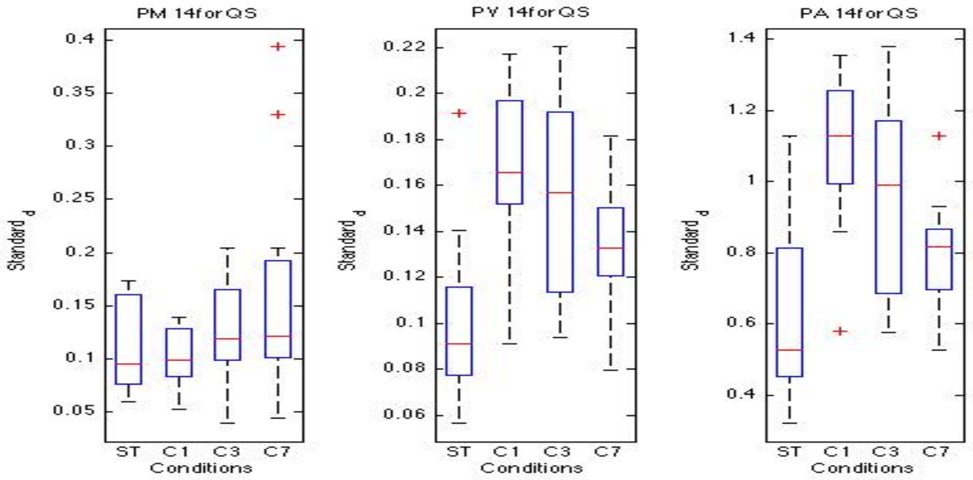

Figure 24. Boxplot for PM 15 (Multi-segment movement of the hips, knees and head)

Appendix II

The boxplots (PM1-15) Close Feet shows the differences in the mean amplitude in PM, PV, and PA.

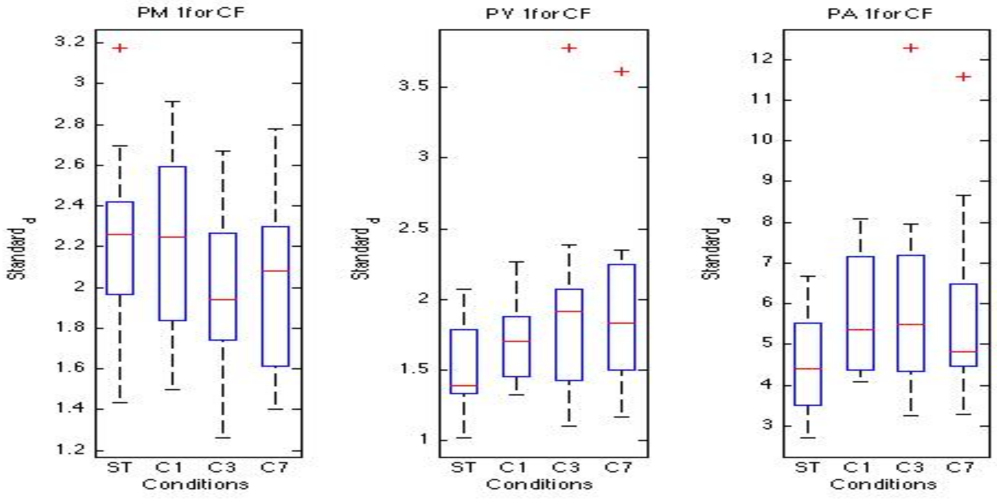

Figure 25. Boxplot for PM 1 (Ankle A/P)

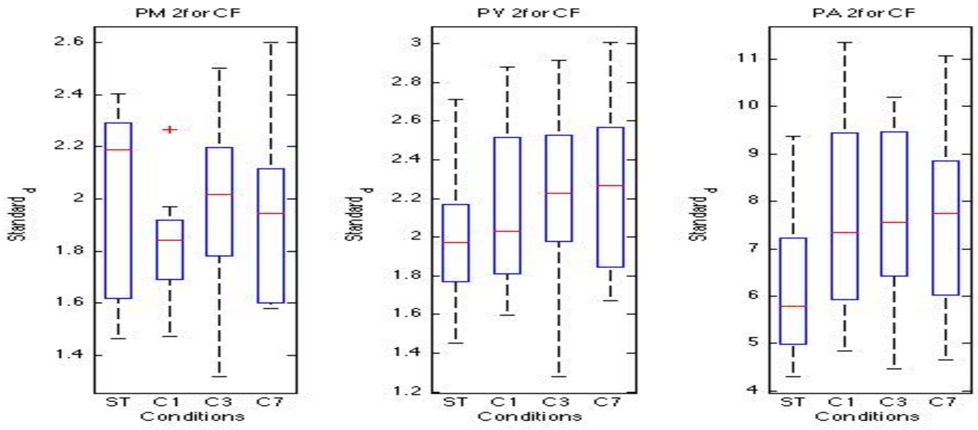

Figure 26. Boxplot for PM 2 (Ankle M/L)

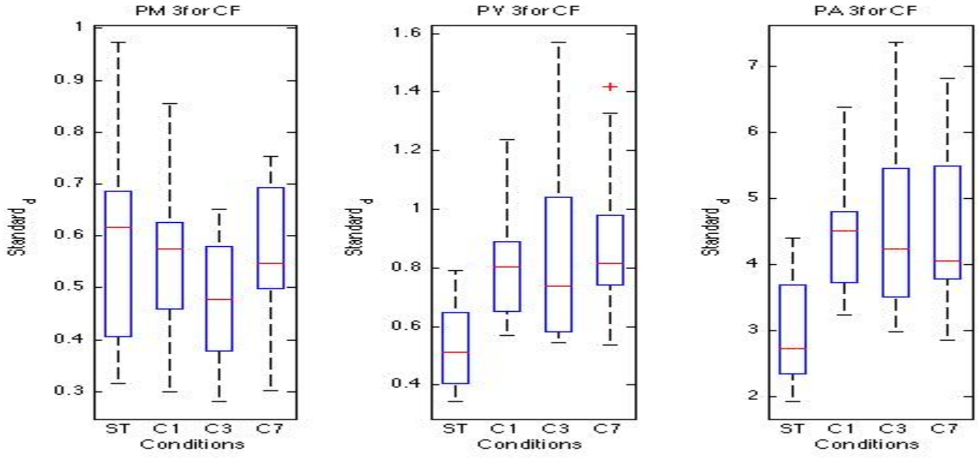

Figure 27. Boxplot for PM 3 (Hip movement in A/P direction)

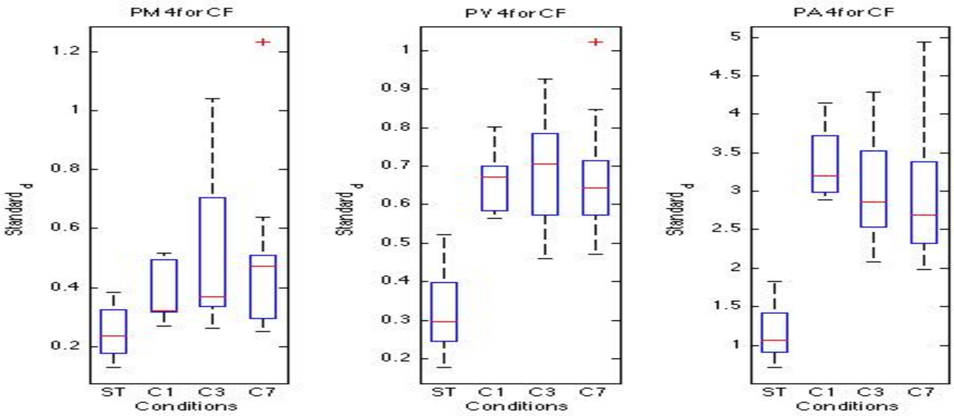

Figure 27. Boxplot for PM 4 (Breathing motion in shoulders)

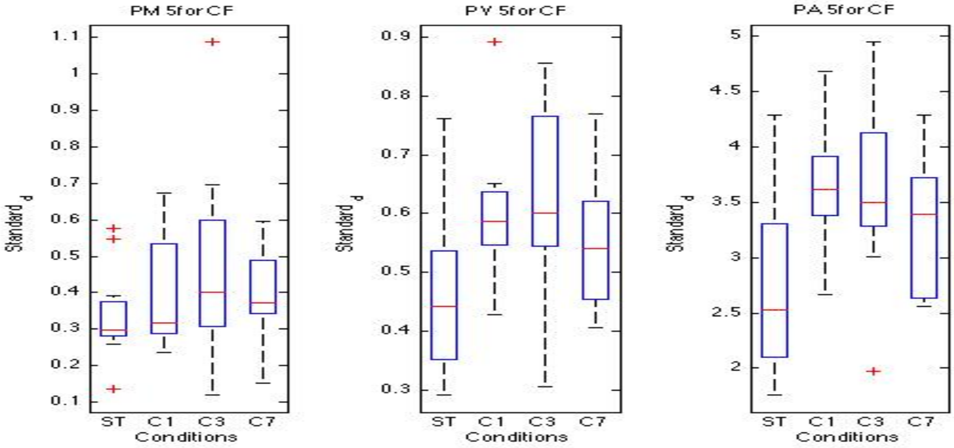

Figure 28. Boxplot for PM 5 (Pelvis rotation around the vertical axis with compensatory shoulder movements)

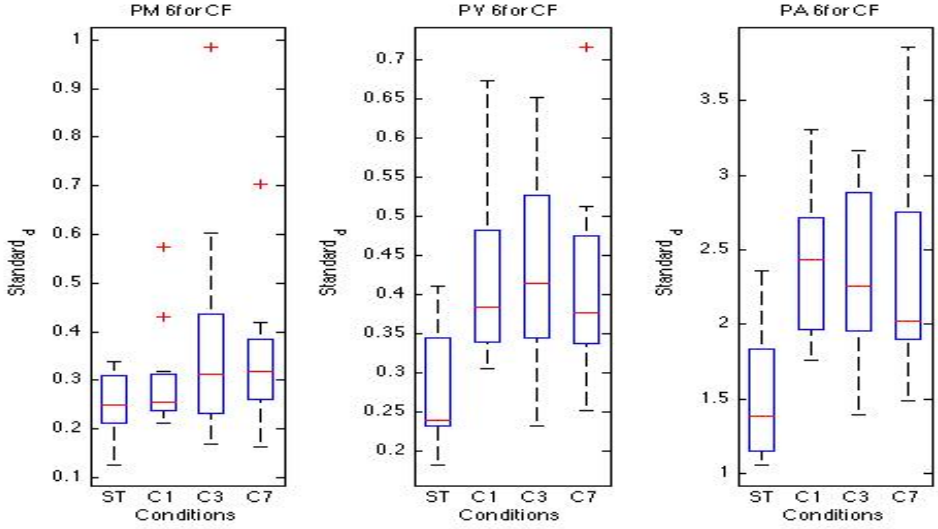

Figure 29. Boxplot for PM 6 (Head nodding)

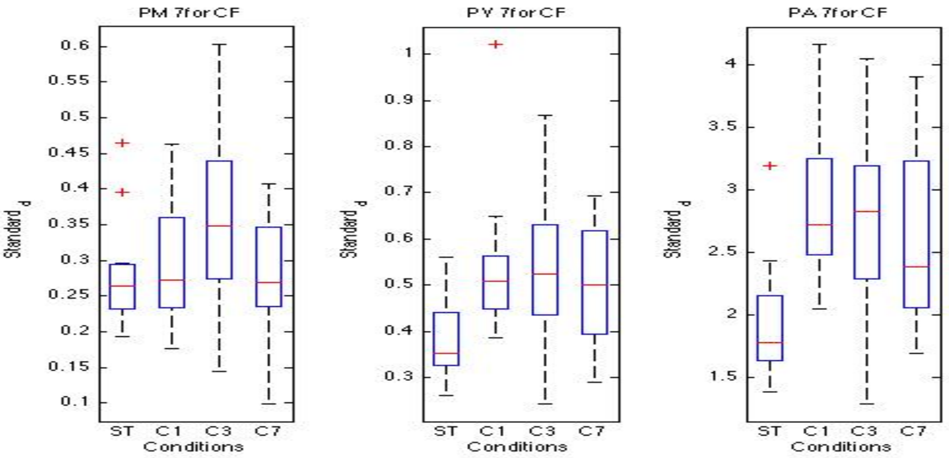

Figure 29. Boxplot for PM 7 (Hip movements in M/L direction)

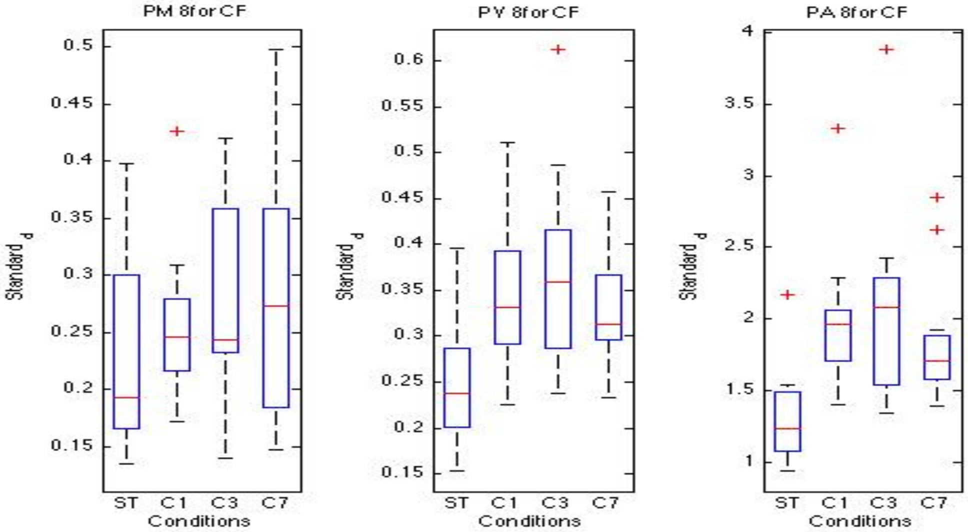

Figure 30. Boxplot for PM 8 (Knee flexion)

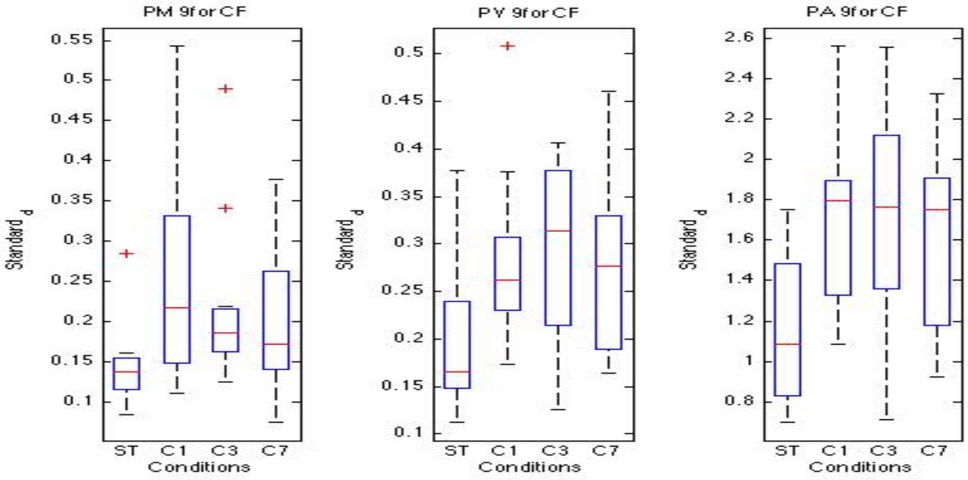

Figure 31. Boxplot for PM 9 (Head movement and shoulder rotation due to head movement)

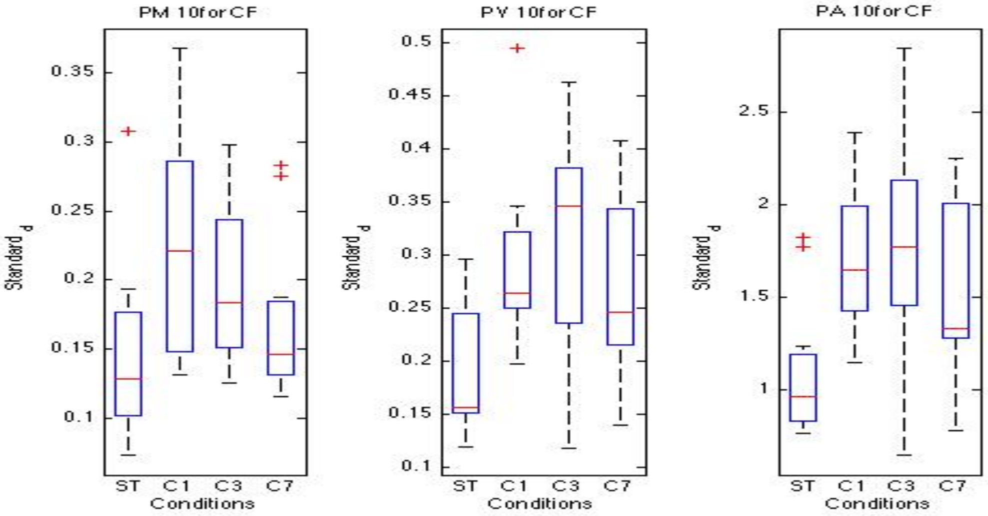

Figure 32. Boxplot for PM 10 (head rotation and shoulder rotation du to head movement)

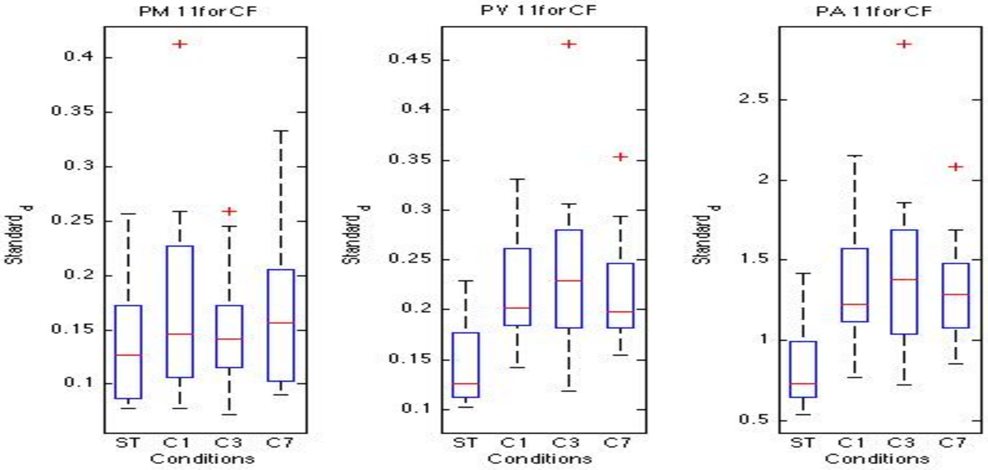

Figure 33. Boxplot for PM 11 (Multi segment movement of the hips, knees and head)

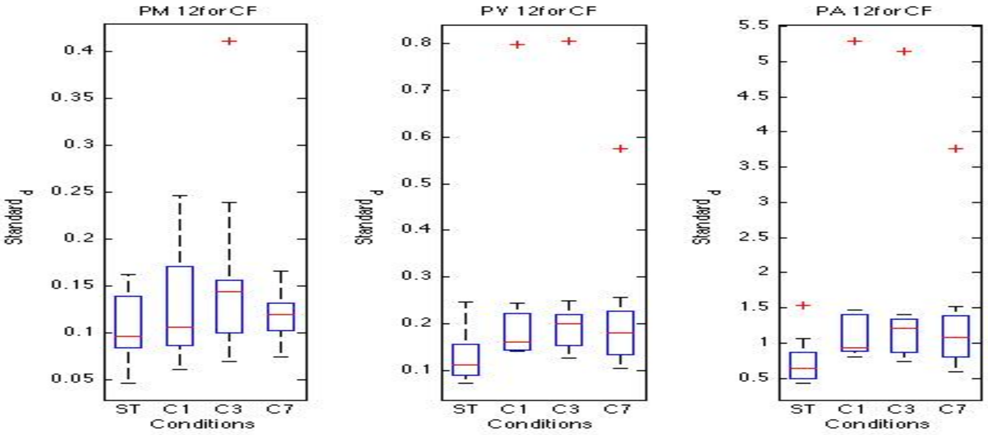

Figure 33. Boxplot for PM 5 (Multi segment movement of the hips, knees and head)

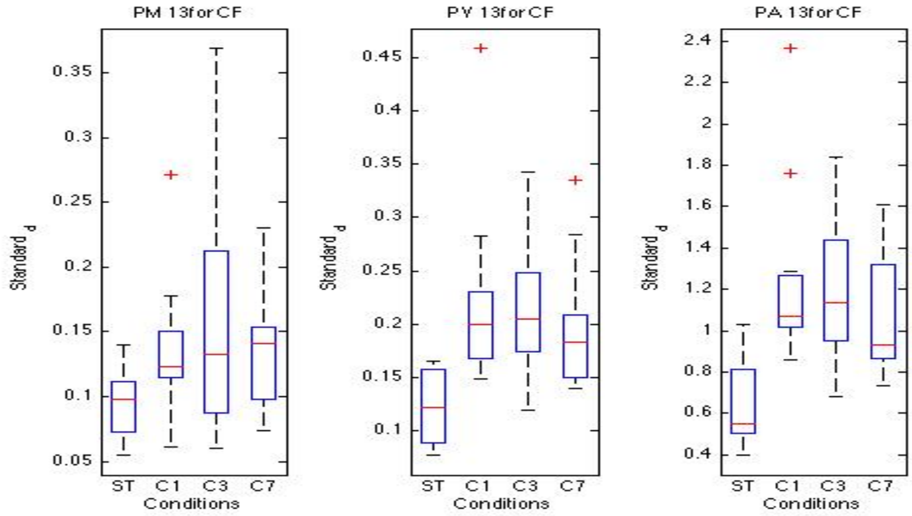

Figure 33. Boxplot for PM 13 (Chest breathing)

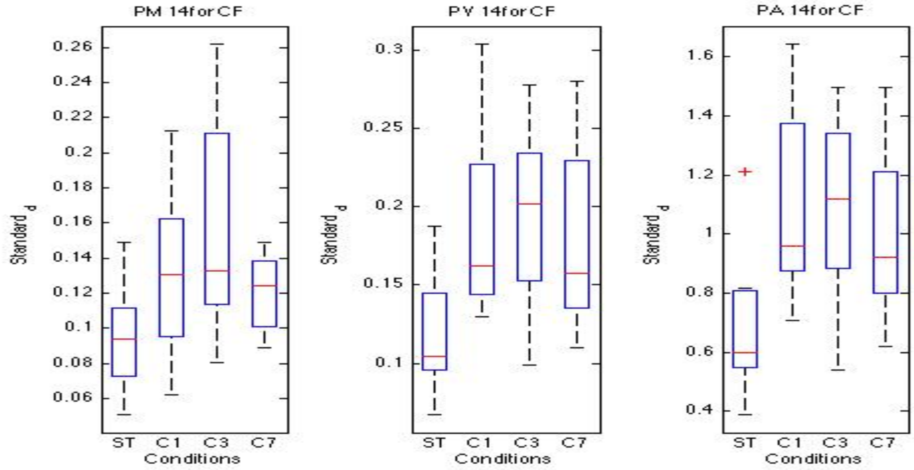

Figure 34. Boxplot for PM 14 (Multi segment movement of the hips, knees and head)

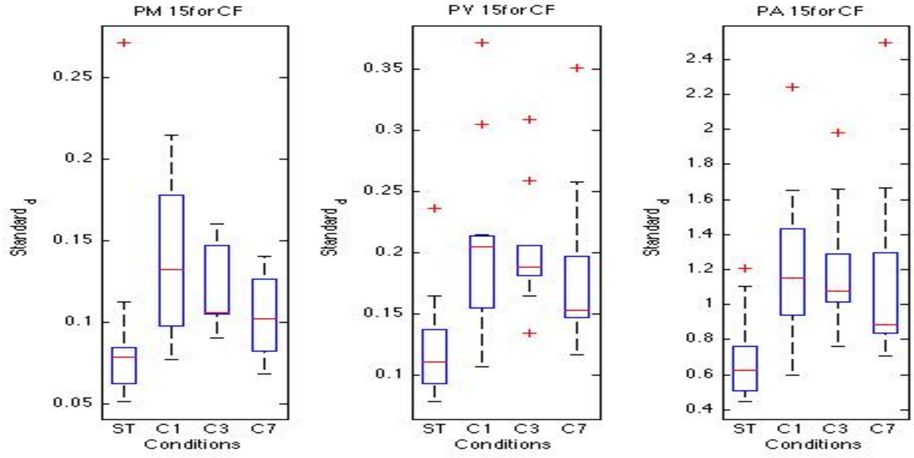

Figure 35. Boxplot for PM 15 (Breathing motion visible in medio-lateral direction)