This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 601003

# BALANCE

**Balance Augmentation in Locomotion, through Anticipative, Natural and Cooperative control of Exoskeletons**

## Deliverable 7.2
## *Proactive and reactive kinematics during various walking manoeuvres*

Due Date of Deliverable: **Month 38**
Actual Submission Date: **Month 40**
Partner Responsible**: URI**

| | |
|---|---|
| **Classification:** | [Public] |
| **Grant Agreement Number:** | 601003 |
| **Contract Start Date:** | 01-01-2013 |
| **Duration**: | 50 Months |
| **Project Coordinator:** | TECNALIA |
| **Partners:** | TECNALIA, ICSTM, CEA-L, TUDLL, UTWEN, ETH, XSENS, URI |
| **Project website:** | BALANCE-FP7.EU |

# Table of Contents

# 1. Executive summary

This deliverable describes the outcomes of experiments with neurologically impaired subjects where proactive and reactive characteristics have been explored during selected walking maneuvers: turning, transition between turning and straight walking, transition between straight walking and turning, gait initiation and gait stopping. In all experiments we used balance assessment robot during over ground walking (BAR-OG) that was developed under Task 7.1 to provide safety and support during training as well as to measure pelvis movement in transversal plane (estimated center of mass displacement in ML and AP directions and pelvis rotation about vertical axis) via its kinematic model and interaction forces between pelvis of a walking subject and BAR-OG. In addition, BAR-OG was also equipped with Optitrack camera while subjects' feet were equipped with IR light reflective markers to track foot placement and to assess stepping responses in terms of step length, step width and step time. Furthermore, we also developed an algorithm that gives an estimation of center of pressure from selected marker positions on feet. By doing this we were able to investigate the relationships between estimated center of mass and estimated center of pressure during explored walking maneuvers. Patients were selected by an experienced physician so that the selected group reflected a wide range of functional abilities that were assessed with standardized functional tests. For reference the experiments were also conducted on intact individuals.

Experimental evaluation has shown that no uniform behavior is present in patients. In general it is true that when walking straight or turning neurologically impaired subjects tend to lengthen the duration of support phase on their better leg which also results in shifting the center of pressure accordingly in the same direction. However, compared to straight walking center of pressure during turning slightly shifts in the direction of turning to account for change in direction of walking. Step length does not share the same tendency. For neurologically impaired subjects there is no rule as to whether step length during straight walking or turning should be longer on impaired or unimpaired side. Patient seem to walk with step length asymmetry that to some extent improves if patient was walking in the direction of longer steps, e.g. if in straight walking left step was longer turning to left reduced step length asymmetry considerably. On the other hand step width pattern was very consistent; when walking straight step width was approximately the same for left and right side, whereas when turning in left (right) direction left (right) step was wider.

Finally initiating and stopping the gait showed that patients have developed mechanisms that enable them to settle at repeatable pattern within several steps. While the number of steps before repeatable pattern was established varies between patients we noticed that utmost three steps were sufficient to make a transition.

# 2. Introduction and objectives

WP 7 that was proposed within the call for extending current FP 7 projects within the BALANCE Enlarged proposal importantly extends the scope of the original BALANCE project to include also people with disabilities resulting from the various neurological impairments, most notably stroke. Disabled importantly differ in their walking and balancing abilities/performance from neurologically intact population. In effect, using the BALANCE exoskeleton and controller principles for supporting neurological patients requires specific understanding of the deficiencies of this group of users, and strategies to identify, compensate and finally overcome such deficiencies. Overall objective of WP 7 is to study how neurological patients maintain their balance during walking and how they can be assisted as needed by an exoskeleton through appropriate control adapted to their specific needs. Consequently WP7 objectives are: 1.) to develop an experimental platform (pelvic robot) that allows studying postural balancing behavior of neurologically impaired subjects (as well as also able-bodied subjects) during over ground walking; 2.) to study postural balance behavior and coping strategies of neurologically impaired subjects during specific gait actions (initiation, accelerating, decelerating, turning, walking backwards) and reaction to perturbations; 3.) to model these behaviors and to develop control approach that can cooperate with particular subjects that suffer from individually specific neurologic impairments; 4.) to evaluate developed controller with selected neurologically impaired subjects in an intrinsically safe environment, using BALANCE exoskeleton and the pelvic robot. Instrumental to reaching the objectives of WP7 is development of the pelvic robot device, which is the subject of this particular deliverable.

This deliverable is focused on Task 7.2 Assessment of proactive balance behavior in neurologically impaired subjects. Specifically, in this task we investigated characteristic responses in impaired subjects during turning, transition between turning and straight walking, transition between straight walking and turning, gait initiation and gait stopping. We concentrated on pelvis movement in transversal plane (estimated center of mass displacement in ML and AP directions and pelvis rotation about vertical axis) that was measured via kinematic model of BAR-OG and interaction forces between pelvis and BAR-OG that were measured with load cells integrated in BAR-OG. In addition, BAR-OG was also equipped with Optitrack camera and subjects' feet were equipped with IR light reflective markers to track foot placement and to assess stepping responses in terms of step length, step width and step time. Also from marker positions we were able to estimate center of pressure and evaluate it in relation with respect to center of mass. This information provided insight into how individual neurologically impaired subjects cope with challenging situations that may evoke instability and increase risk of falling. From the perspective of controlling exoskeleton robot in its efforts to augment balance during challenging maneuvers the outcomes of the experiments reported in this deliverable will provide guidelines how the exoskeleton should cooperate with neurologically impaired subjects in terms of proactive balancing.

First we provide brief description of BAR-OG design and its main characteristics when used with subjects during subsequent experiments. We then present experimental design and experimental methods that were applied during the experiments as well as data processing methods and protocol of experiments. Next we list in a table the pathologies of selected patients together with corresponding outcomes of functional tests. Finally we conclude with presentation of results that addressed pelvis movement in transversal plane and corresponding interaction forces between pelvis and BAR-OG, relationship between estimated center of mass (COM) and estimated center of pressure (COP) and selected spatio-temporal characteristics in various movement maneuvers.

# 3. Methods

## 3.1 BAR-OG

Balance assessment robot during over ground walking (BAR-OG) is composed of two primary subsystems: i) mobile platform (MP) and ii) pelvic manipulator (PM). Primary aim of mobile platform is to provide over ground mobility in two DoF (forward movement and turning) and to ensure rigid support basis and appropriate attachment locations for the pelvic manipulator. MP is designed as U-shaped rigid steel frame with steel angular reinforcements designed to sustain loading associated with delivering perturbations. It is supported at the front with two castor wheels at left and right side respectively that enable angular motion of the mobile platform and two motorized wheels that are positioned at such location so that the line connecting their axes is aligned as close as possible with frontal plane aspect of the subject. In this arrangement the subject may turn at spot without having the need to step forward or backward. There are six universal joints located on the steel frame that further connect to PM. Two universal joints are located in the cylinders on the left and right side of the MP and connect to vertical rods of the PM. The remaining four universal joints are located at the front of the MP frame and connect to distal ends of linear actuators of PM. Linear actuators are composed of DC motors with absolute encoders that connect to linear ball bearings. The proximal ends of the linear actuators are connected to vertical rods of PM via spherical ball joints so that the left pair of linear actuators connects to vertical rod on the left and the right pair of linear actuators connects to vertical rod on the right. When actuated each pair of linear actuators deliver two DoF actuated movement to vertical rod it is connected to. At the top both vertical rods are connected by pelvic element (PE) with pelvic brace (PB) via spherical ball joints that are kept free to slide along the narrower end of both vertical rods. Both ends of PE are equipped with a pair of perpendicularly arranged load cells that are on the inside attached to pelvic tubing made of carbon fibers i.e. PE and PB. When pelvis is tightly embraced each pair of load cells measures interaction forces between the subject's pelvis and the PM in anterior/posterior (AP) and medio/lateral (ML) direction. Altogether PM alone provides six DoF movement: i) four DoF from vertical rods are diminished by one DOF due to PE connecting both tops to finally provide actuated pelvis AP displacement, actuated pelvis ML displacement and actuated pelvis rotation, ii) sliding motion of spherical ball joints extends three active DoF with three passive DoF i.e. pelvis tilt in sagittal plane, pelvis list in frontal plane and passive pelvis vertical displacement. Operation characteristics of BAR-OG are determined through admittance-based scheme which enables rendering of desired mechanical impedance. Mechanical impedance can be set to minimal values (transparent mode) or can be programmed to provide desired level of assistive forces to a walking subjects' pelvis. Further, the device enables imposition of mechanical perturbations in various directions thus facilitating studying of postural responses during walking. BAR-OG is shown in Figure 1 and detailed overview of BAR-OG composition as well as control scheme design and implementation is available in Deliverable D7.1.

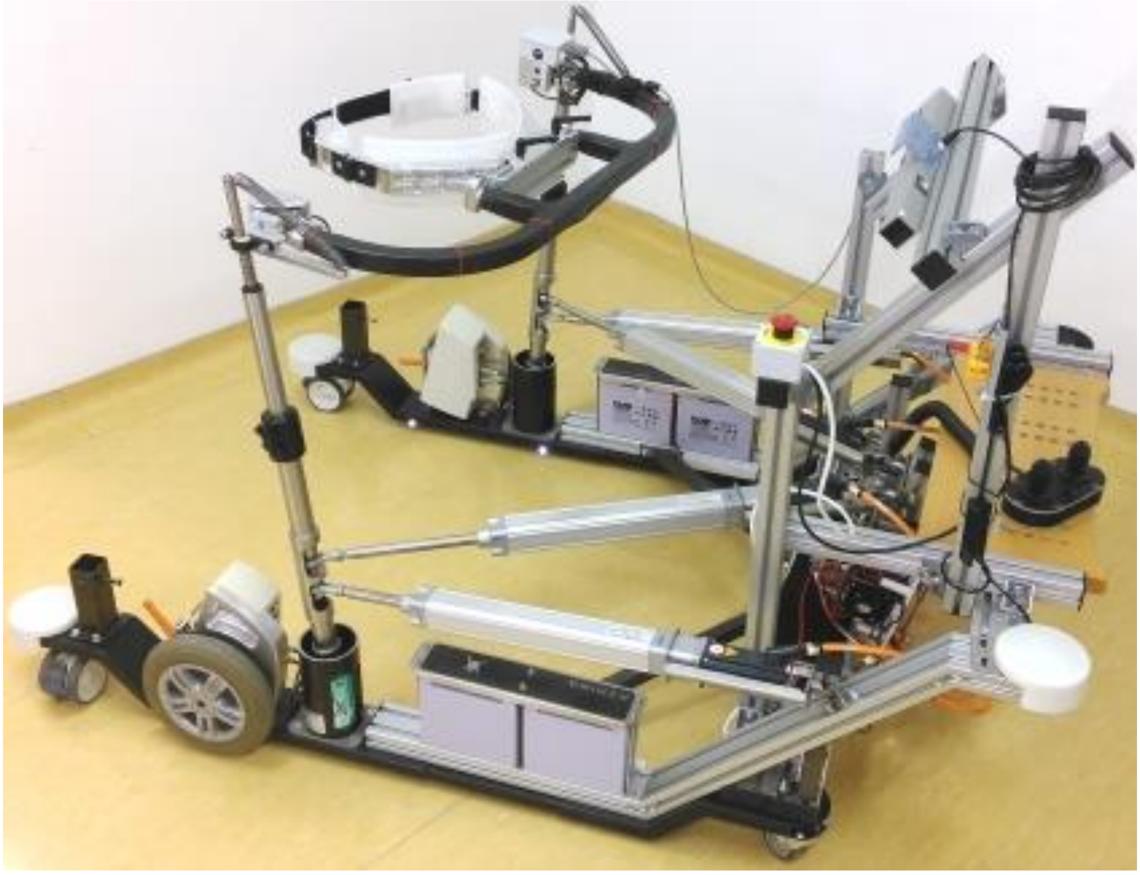

*Figure 1. BAR-OG*

## 3.2 Experimental design

In current deliverable we used balance assessment robot during walking BAR-OG that was developed within deliverable D7.1 to identify selected gait characteristics during

- steady straight walking
- steady turning in left and right direction
- transition between straight walking and turning left and right
- transition between turning left or right and straight walking

In particular we were interested in characteristics of

- pelvis movement in transversal plane (pelvis displacement in ML and AP directions and pelvis rotation about vertical axis)
- interaction forces/moment between subject and BAR-OG in transversal plane
- stepping responses in terms of step length, step width and step time
- relationship between estimated center of mass and estimated center of pressure

Pelvis movement in transversal plane (pelvis displacement in ML and AP directions and pelvis rotation about vertical axis in CW/CCW direction) were directly obtained from movement of central point of pelvis element of BAR-OG. Since this point is approximately aligned with subject's center of mass we will refer to it as the estimated center of mass and will be abbreviated as eCOM. Interaction forces between subject's pelvis and pelvis element of BAR-OG were measured by two pairs of force sensors.

Beside tracking pelvis position (eCoM) through the kinematic model of pelvis manipulator of BAR-OG and interaction forces between subject and pelvis element of BAR-OG, subject's feet were equipped with reflective markers (medial malleoli, 1$^{st}$ metatarsal joint and 4$^{th}$ metatarsal joint) and BAR-OG was equipped with Optitrack camera (NaturalPoint, Inc.) to also investigate stepping responses in terms of step length, step width and step time. Since the Optitrack camera was not aligned with the coordinate frame of BAR four additional markers were placed to a known positions on moving platform of BAR-OG to determine transformation matrix between the coordinate frame of BAR-OG and the Optitrack camera. We then calculated left (right) step length as AP distance between ankle markers at the moment of left (right) foot strike while left (right) step width was defined as the ML distance between the same markers at the moment of left (right) foot strike. Similarly, left (right) step time was defined as the time between consecutive right (left) foot strike and left (right) foot strike.
Since all experiments were conducted during over ground walking we were not able to measure center of pressure. However we developed an algorithm that has limited capabilities (predominantly in the medio-lateral direction) of estimating the center of pressure from the movement of reflective markers of subject's feet, hence estimated center of pressure (eCOP).

## 3.3 Data processing

### 3.3.1 COP estimation

The COP estimation was calculated using Optitrack motion capture system, where the camera was located in front of the subject during walking, focused on subject's feet. Four reflective markers were attached on each leg – two on the ankle joint and two in the front of the foot as shown in Figure 2. The camera recorded the x, y and z positions of each marker, which were then offline processed to determine an estimated COP.

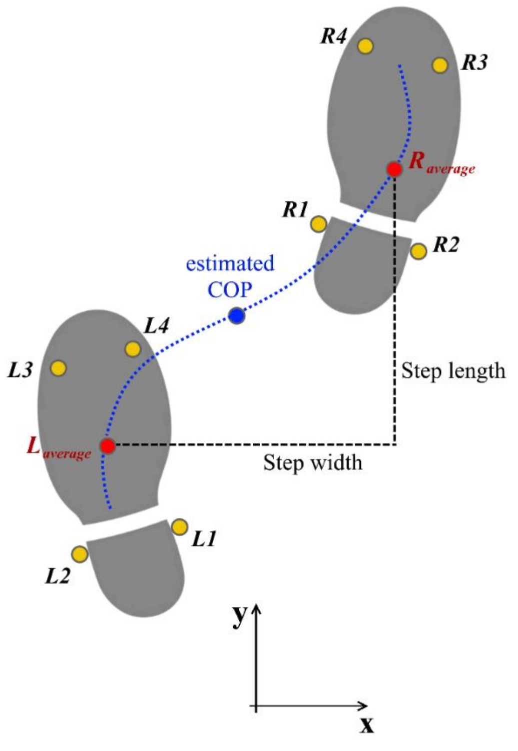


*Figure 2. Using reflective markers to estimate COP, step length and step width.*

In the offline processing, first we needed to identify whether the foot was in contact with the ground (i.e. grounding process). For that, the thresholds $h_z$ for each marker were determined from the marker z coordinate. We define parameters $a_i$ and $b_i$ that represent grounding (i.e. being in contact with the ground) of each marker: $a_i$ parameters for the left foot markers and $b_i$ parameters for the right foot markers. They are either 0 or 1 depending on whether the marker z coordinate was above or below the vertical threshold $h_{zi}$:

$$a_i(t) = \begin{cases} 0 & if \quad L_{zi}(t) \geq h_{zi} \\ 1 & if \quad L_{zi}(t) < h_{zi} \end{cases}$$

$$b_i(t) = \begin{cases} 0 & if \quad R_{zi}(t) \geq h_{zi} \\ 1 & if \quad R_{zi}(t) < h_{zi} \end{cases}$$

The estimation of COP is then calculated via following equations for each coordinate of COP:

$$COP_x(t) = \frac{\sum_{i=1}^{N}[a_i(t)\, L_{xi}(t) + b_i(t)\, R_{xi}(t)]}{\sum_{i=1}^{N}[a_i(t) + b_i(t)]}$$

$$COP_y(t) = \frac{\sum_{i=1}^{N}[a_i(t)\, L_{yi}(t) + b_i(t)\, R_{yi}(t)]}{\sum_{i=1}^{N}[a_i(t) + b_i(t)]}$$

which in simplification means that the COP is located at the average position of all grounded markers.

In order to calculate step length and width, at first the double stance gait sub phase needed to be detected, which was done by observing z coordinate of the average marker for each foot and its velocity. The average markers for left and right foot are defined as:

$$\vec{L}_{average} = \frac{1}{4}\left(\overrightarrow{L_1} + \overrightarrow{L_2} + \overrightarrow{L_3} + \overrightarrow{L_4}\right)$$

$$\vec{R}_{average} = \frac{1}{4}\left(\overrightarrow{R_1} + \overrightarrow{R_2} + \overrightarrow{R_3} + \overrightarrow{R_4}\right)$$

Step length (SL) and step width (SW) were then extracted from the x and y coordinates of the left and right average markers at the time of double stance (DS) as follows:

$$SL_i = \left| {L_{average}}_y^{DS_i} - {R_{average}}_y^{DS_i} \right|$$

$$SW_i = {R_{average}}_x^{DS_i} - {L_{average}}_x^{DS_i}$$

Step time (ST) was extracted from the data as an interval between two consecutive double stance gait sub-phases.

$$ST_i = t_{DS_i} - t_{DS_{i-1}}$$

The presented method for COP estimation is rather rudimentary, however it is a convenient tool as during over ground walking done in these experiments force plates could not be used.

However, COP estimation calculation is highly dependent on selected thresholds for markers. In order to explore how useful the proposed method could be we performed some walking experiments on instrumented treadmill in order to compare the measured COP with its estimation. Figure 3 shows an example, where an estimated COP satisfactorily fits with a measured COP, while in Figure 4 the thresholds were selected differently, which can be seen in noticeable COP mismatch in both examples. Nevertheless, the sensitivity of eCOP is primarily in the anterior-posterior direction while in the medio-lateral direction reliable estimate can be obtained.

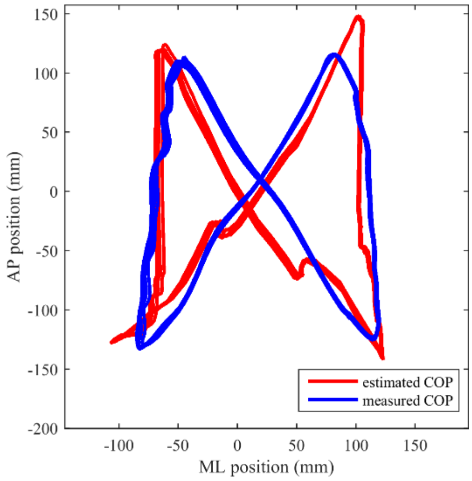


*Figure 3. An example of satisfactory fitting between the estimated COP and the measured COP.*

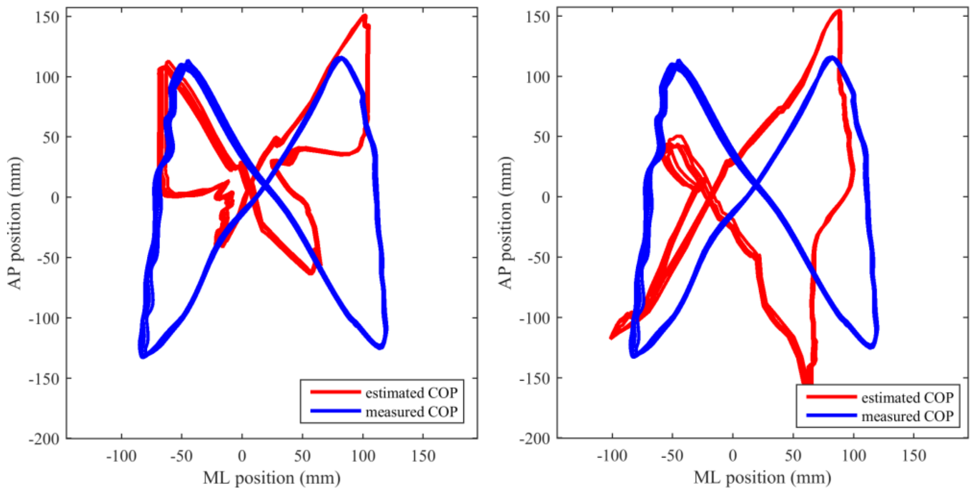


*Figure 4. Examples of mismatch between the estimated COP and the measured COP.*

### 3.3.2 Data processing

In all experiments all data were first normalized into strides where stride was defined with two consecutive foot strikes of the same leg. Left foot strike was determined by foot switch whereas the right foot strikes were determined as the local maxima of the ankle marker positions in the anterior/posterior direction.

### 3.3.3 Experimental protocol

The session started with short acclimation period where the subject was given the opportunity to get acquainted with BAR-OG and to experience different modes of walking. Then the subject was equipped with reflective markers and firmly fastened within PB. All subjects wore special belt that accommodates shape according to anthropomorphic characteristics of each subject's pelvis and in this way ensures that subjects were evenly fastened around waist within PB while also inhibiting relative movement between subject's pelvis and PB. This guaranties optimal force transmission between the subject and the PM which is imperative for proper operation of admittance control. Since we assumed that balance responses particularly in transition experiments would span over several steps we observed responses over a series of consecutive steps.

## 3.4 Subjects

### 3.4.1 Healthy subjects

Seven neurologically and orthopedically intact adults of similar stature and average age of 33.4 ± 8.5 years, average body weight of 80.1 ± 11.6 kg and average height of 180.6 ± 5.3 cm were invited to participate in a study. Speed of BAR-OG i.e. gait velocity and the radius of turning were in healthy subjects experimentally explored and set at 0.85 m/s and 1.6 m respectively and remained unchanged throughout the experiments.

### 3.4.2 Patients

Five patients with different pathologies and gait functionalities were invited to participate in this study. Their information is listed in Table 1.

*Table 1. Neurologically impaired subjects (P1 – P5) – pathologies, functional tests and experimental parameters.*

| | P1 | P2 | P3 | P4 | P5 |
|---|---|---|---|---|---|
| Age (years) | 41 | 76 | 53 | 70 | 30 |
| Time after injury | 2 years | 5 months | 7 months | 10 months | 11 months |
| Diagnosis - stroke | Right-side hemiparesis | Left-side hemiparesis | Left-side hemiparesis | Right-side hemiparesis | Discrete right-side hemiparesis |
| BBS | 53/56 | 50/56 | 55/56 | 50/56 | 56/56 |
| 6 min test | 185 m | 330 m | 375 m | 267 m (with cane) | 385 m |
| 10 m test | 21.27 s | 7.8 s | 7 s | 13.8 s | 7.2 s |
| Up and go test | 16.22 s | 12.5 s | 9 s | 10.8 s | 8.5 s |
| FAC (Functional ambulation category | 5 | 5 | 5 | 5 | 5 |
| mFIM (motor functional independence measure) | 75 | 80 | 79 | 82 | 75 |
| cFIM (cognitive functional independence measure) | 22 | 31 | 29 | 33 | 34 |
| Four square step test | 19.62 s | 19.5 s | 18 s | 18 s | 11 s |
| Speed of walking in tests | 0.3 m/s | 0.3 m/s | 0.45 m/s | 0.55 m/s | 0.8 m/s |
| Radius of rotation in tests | 1.6 m | 1.6 m | 1.6 m | 1.6 m | 1.6 m |
| Stiffnes of BAR-OG in tests | 150 N/m | 25 N/m | 25 N/m | 150 N/m | 25 N/m |

Appropriate speed of BAR-OG i.e. gait velocity and the radius of turning were in patients determined experimentally for each individual patient separately and were not changed afterwards.

# 4. Results

## 4.1 Turning

Primary aim of experiments related to straight walking and turning as well as transitions between turning and straight walking was to investigate consistencies in pelvis movement, especially pelvis rotation in transversal plane, that accompany selected walking conditions. In particular we were interested in the relationship between COM and COP as well as step length, step width and step time characteristics that are present in steady state or occur in a series of steps in response to transitions between two walking conditions.
The turning experiments were performed by walking in circles, alternating between turning to the right (clockwise direction) and turning to the left (CCW direction). The radius R of the circle was 1.6 m and the distance L between two consecutive turnings was at least 4 m of straight walking. The linear walking speed was set to 0.85 m/s for healthy subjects, while it was selected for each patient individually according to Table 1. After covering straight walking distance L, the turning was triggered by the left foot switch. After that, the BAR-OG operator performed around 1.5 circles. Each turning was repeated at least 4 times. The path for the turning experiment is shown in Figure 5.

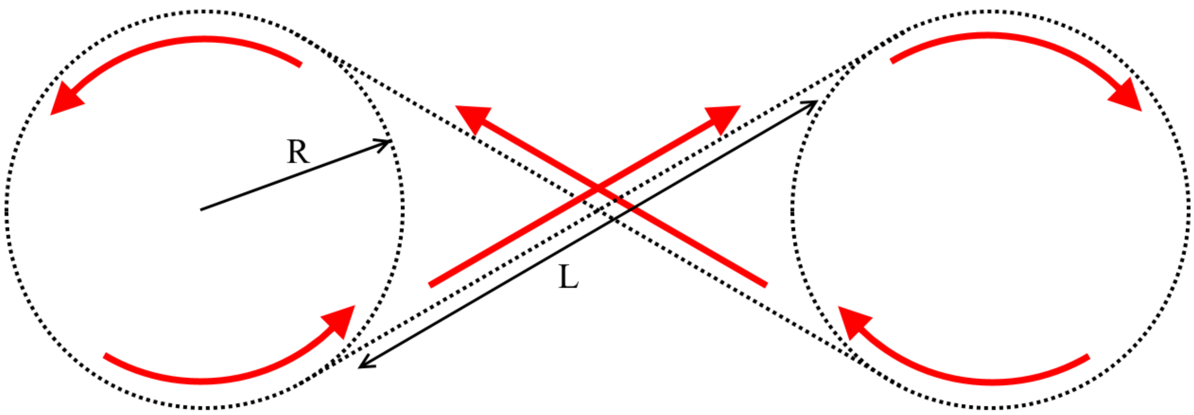


*Figure 5. Turning experiment path.*

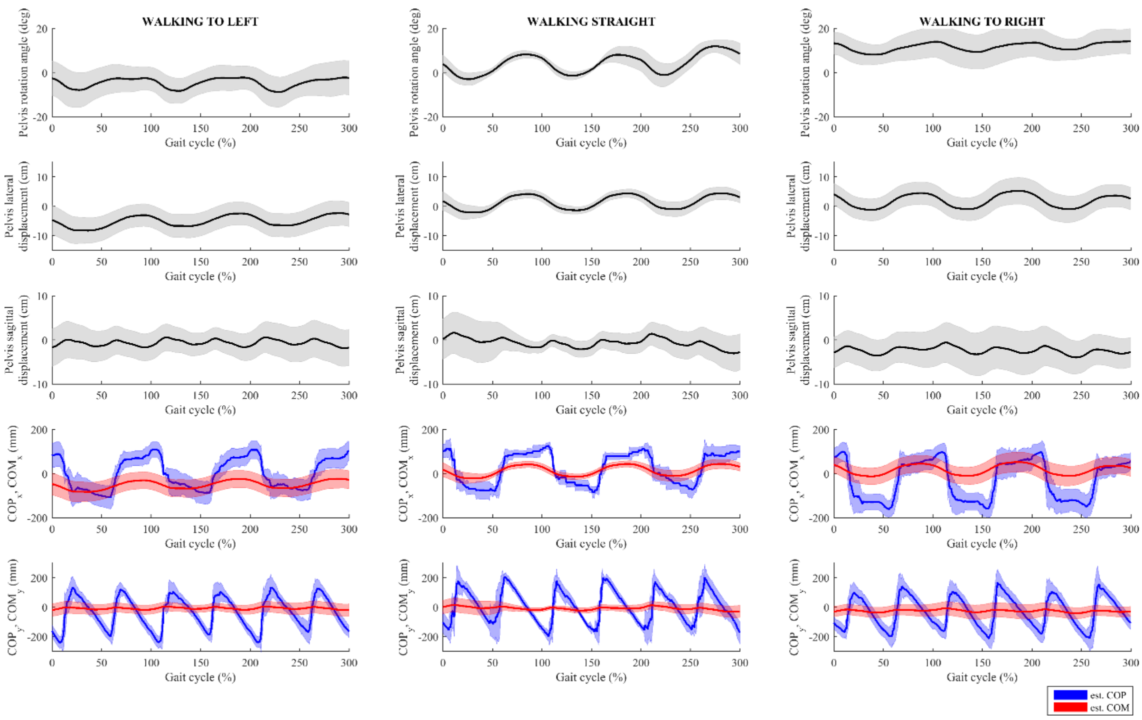


*Figure 6. Representative healthy subject, steady state*

Figure 6 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral directions for a single representative healthy subject while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that compared to walking straight continuous turning had largest effect on pelvis rotation and COP movement in medio/lateral direction and was less evident elsewhere. While pelvis rotation displays well repeatable oscillatory movement approximately around middle rotation when walking straight, in turning we observe consistent offset in pelvis rotation in the direction opposite to the direction of turning, i.e. right pelvis rotation was present when turning left and vice versa left pelvis rotation was present when turning right. Similarly, when walking straight COP and COM in medio/lateral direction were oscillating around the same central position whereas when turning COM shifts with respect to COP in the direction of turning (inward), i.e. when turning left COM shifted more to the left with respect to COP and it shifted more to the right with respect to COP when turning right. On the other hand all three experimental tests exhibit similar pelvis displacement and COM and COP movement in anterior/posterior direction. Nevertheless compared to straight walking turning (left or right) was characterized with larger standard deviations which indicate larger variability in pelvis movement and movement of COM and COP.

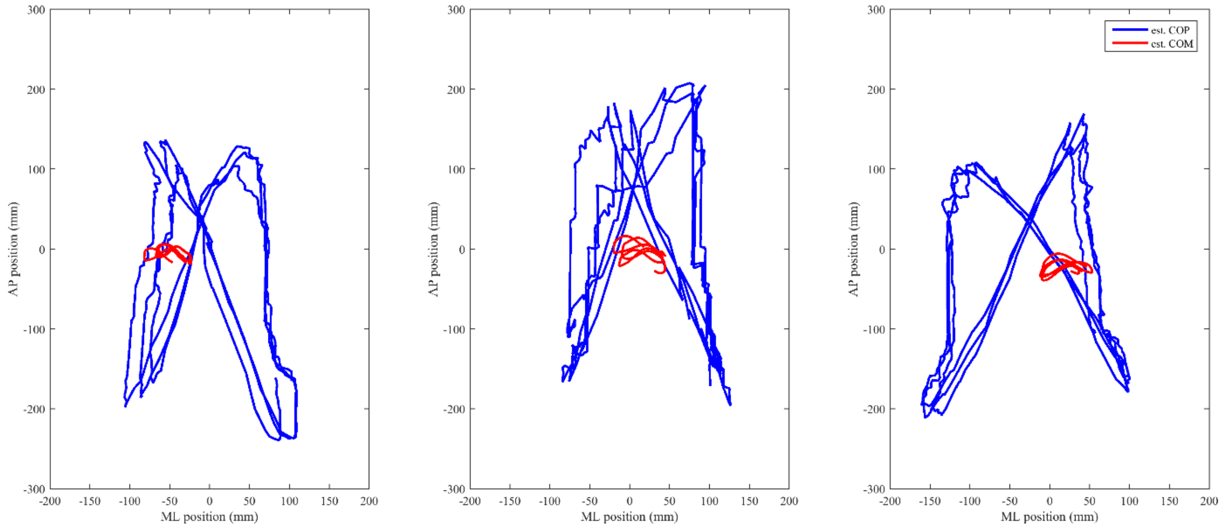


*Figure 7. Representative healthy subject, steady state*

Figure 7 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a single representative healthy subject while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. When walking straight center of COM movement and center of COP movement were approximately aligned whereas when turning COM shifted with respect to COP in the direction of turning (inward), i.e. when turning left COM shifted more to the left with respect to COP and it shifted more to the right with respect to COP when turning right.

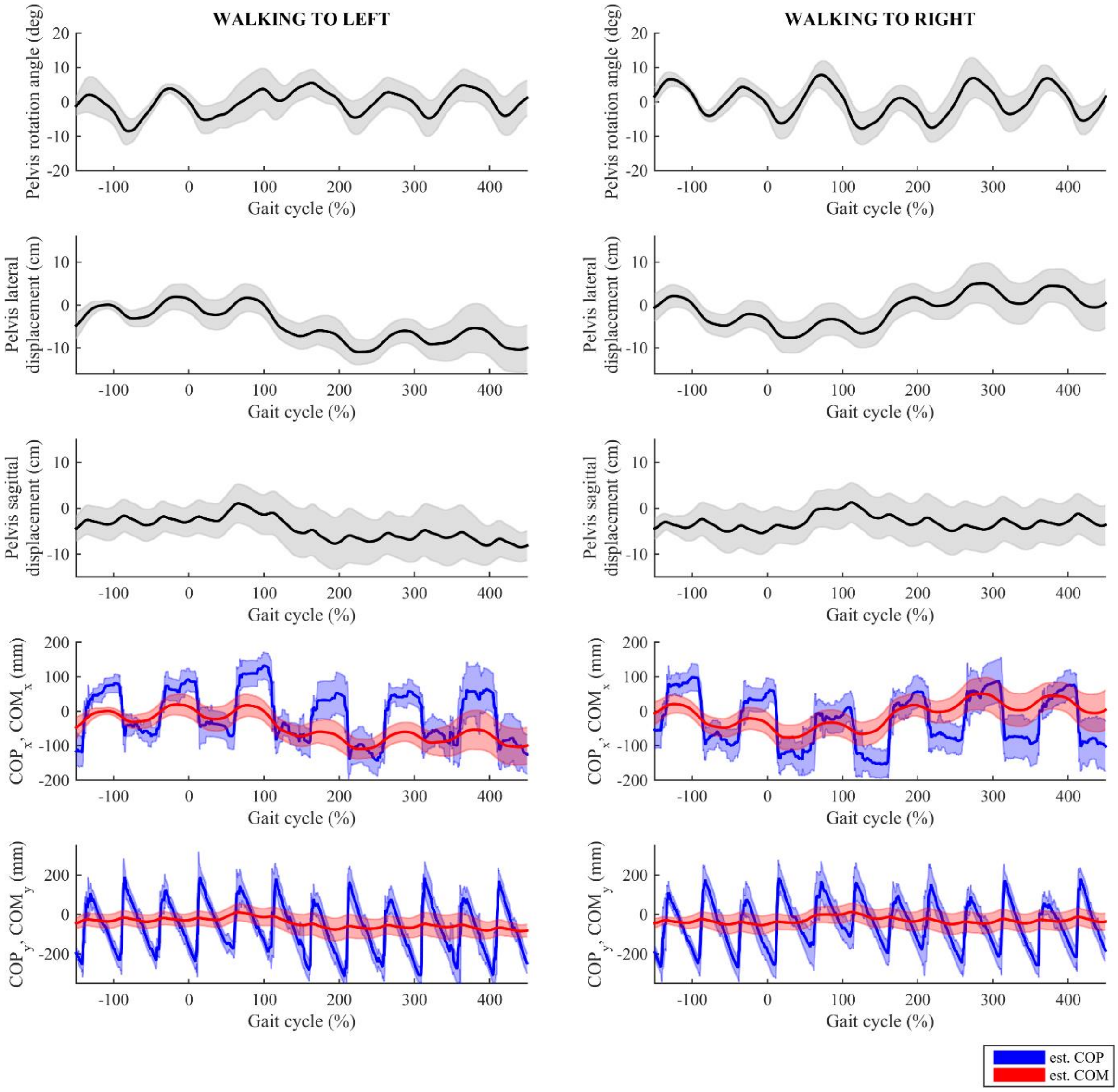


*Figure 8. Representative healthy subject, transients at the beginning of rotation (at 0 %)*

Figure 8 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction of a single representative healthy subject during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after initiating turning left (left panels) or right (right panels). We notice that at first aligned centers of COM and COM movement in medio/lateral direction gradually deviated apart after turning was induced. Although the change in the direction of walking evidently disturbed pelvis movement it did not elicit consistent changes in pelvis movement in the first four strides. However it did immediately influence the relationship between COP and COM movement. When turning was induced to the left COM displaced more to left with respect to COP and when turning was induced to right COM displaced more to right with respect to COP and remained unchanged thereafter.

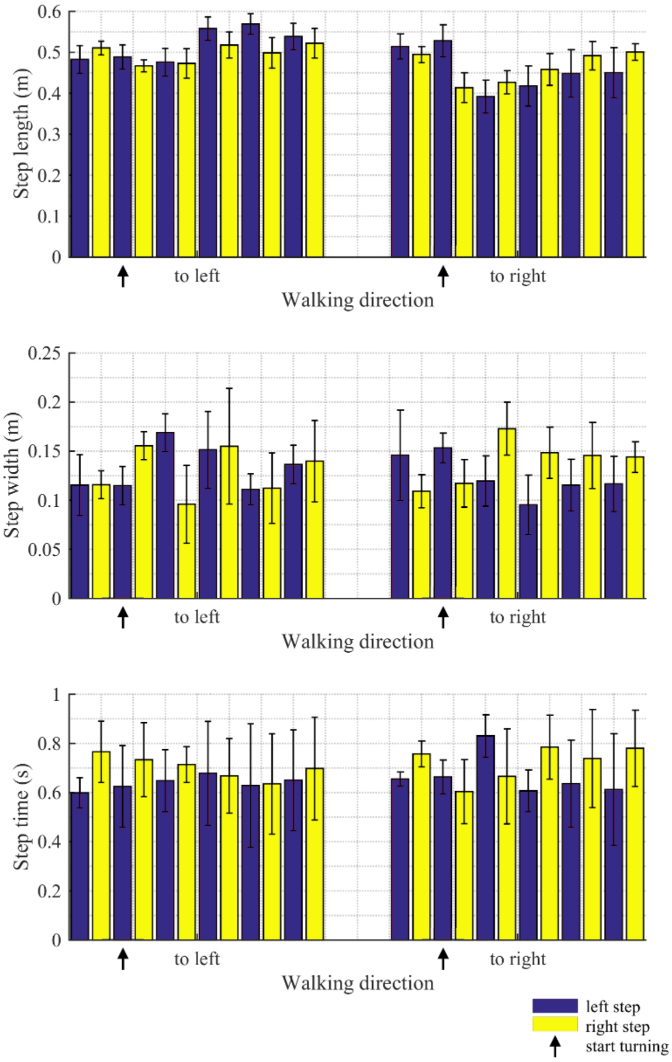


*Figure 9. Representative healthy subject, transients at the beginning of rotation*

Figure 9 shows step lengths, step widths and step times during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after turning left (left panels) or right (right panels) was initiated - in a single representative healthy subject. In selected subject initiating the turning to the left did not affect the step length immediately after transition but after three steps the left step was consistently longer than successive right step. On the other hand it did introduce large variability in step width and elicited more symmetry in step time compared to faster left and slower right steps before the onset of transition. Also, initiating transition to the right immediately reflected in shorter step lengths with right step being somewhat longer than successive right step. Transition from straight walking to turning to the right also reversed the step width pattern – after the transitions right step becomes wider than successive left step.

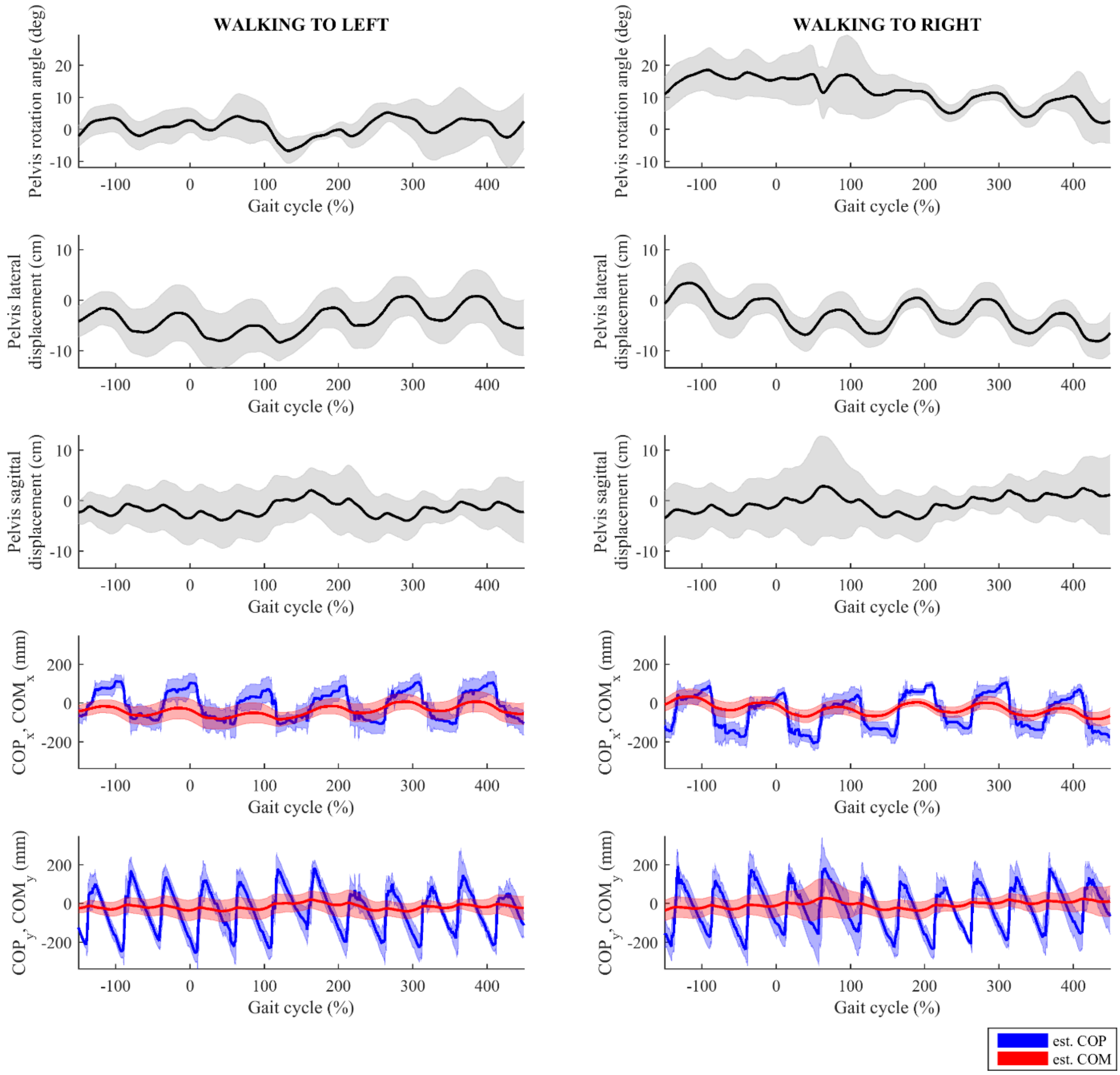


*Figure 10. Representative healthy subject, transients at the end of rotation (at 0 %)*

Figure 10 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction of a single representative healthy subject during transition between turning left (left panels) or right (right panels) and straight walking - immediately before and after initiating straight walking. We notice that misalignment between centers of COM and COM movement in medio/lateral direction gradually diminished after the transition and after four gait cycles settled with both centers COM and COP being approximately aligned. On the other hand transition between turning and walking straight did not elicit consistent changes in pelvis movement in the first four strides.

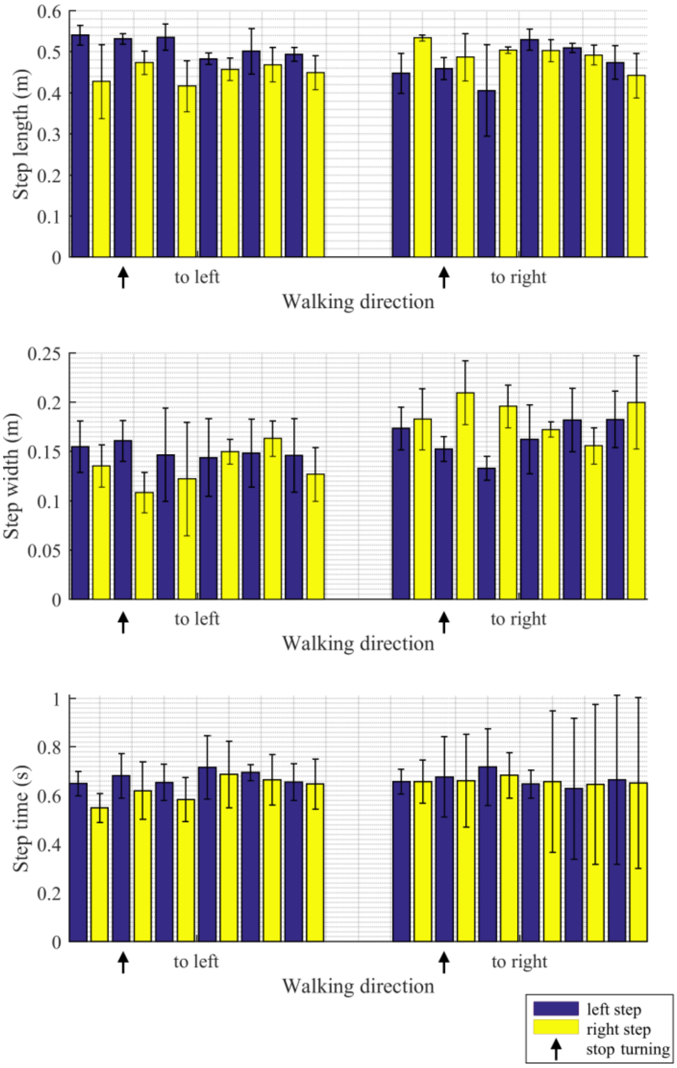


*Figure11. Representative healthy subject, transients at the end of rotation*

Figure 11 shows step lengths, step widths and step times during transition between turning left (left panels) or right (right panels) and straight walking - immediately before and after initiating straight walking - in a single representative healthy subject. We observed that prior to the onset of transition step length asymmetry was present in both cases – left step was longer when turning left whereas when turning right step was longer. After transition both cases display approximately equal step lengths. On the other hand transition between turning and walking straight did not elicit consistent changes in step width or step time.

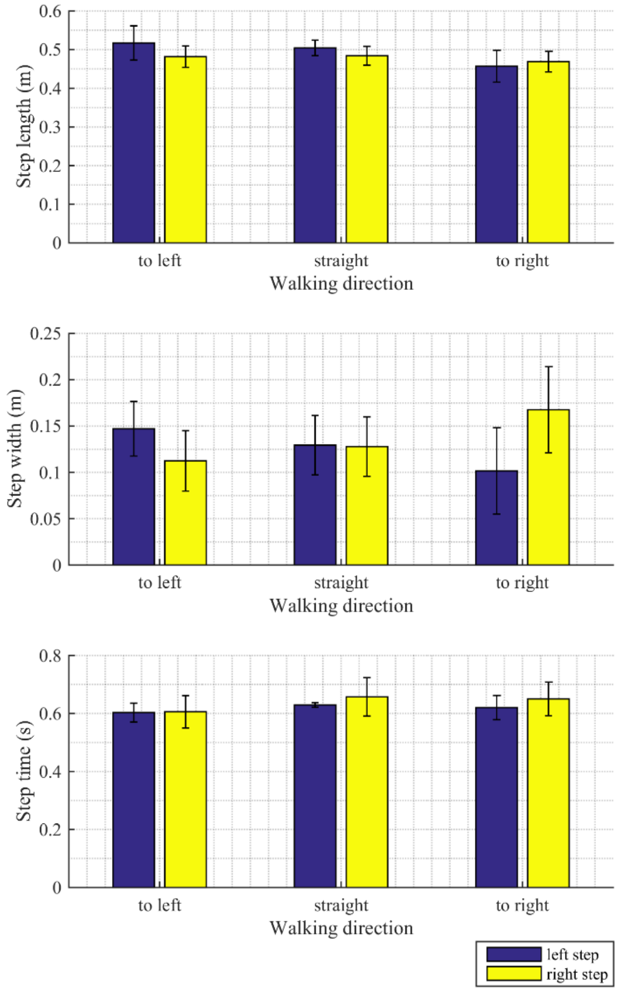


*Figure 12. Group average of 7 healthy subjects, steady state*

Figure 12 shows average step lengths, average step widths and average step times for a group of healthy subjects while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that continuously turning left was characterized with left step being longer and wider whereas when turning right asymmetry was reversed so that right step was longer and wider. When walking straight left and right step lengths and widths were approximately equal. On the other hand step times in all three cases displayed tendency toward faster left step.

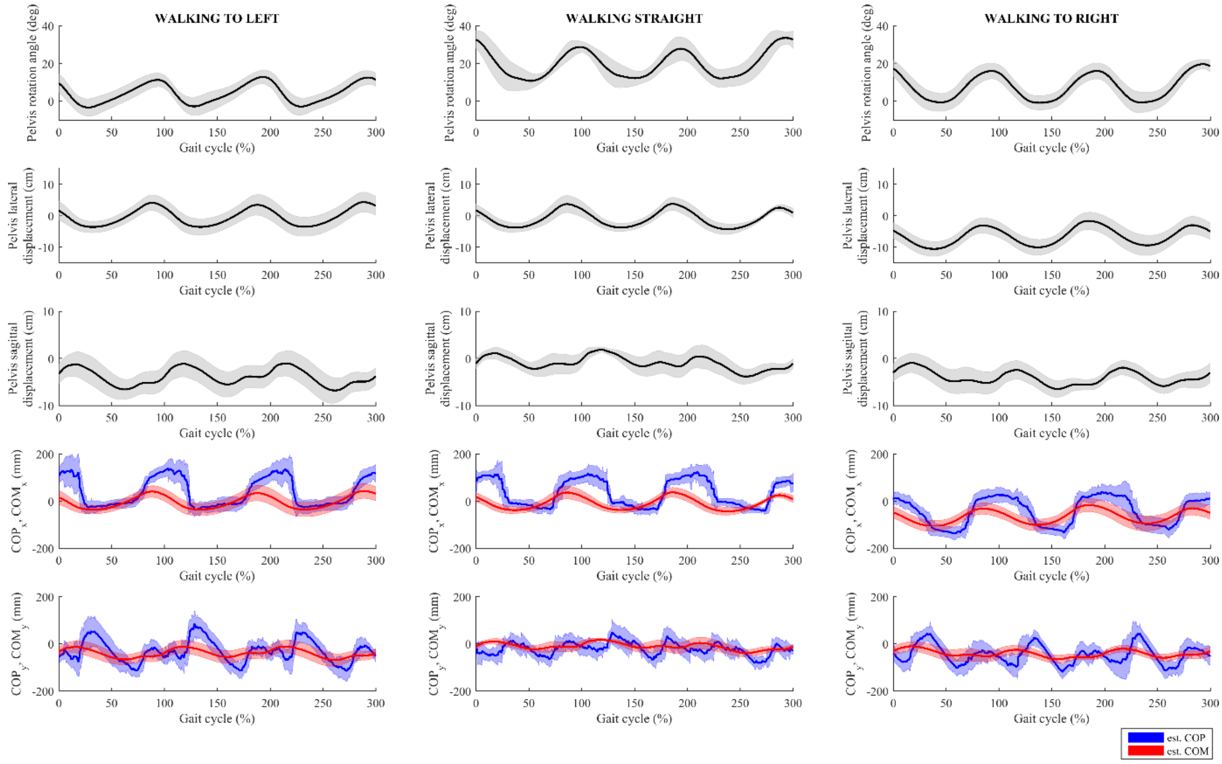


*Figure 13. Stroke subject P1, steady state*

Figure 13 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P1 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that straight walking was in this subject characterized with substantial pelvis rotation up to 40° in CCW direction, whereas in both cases of turning pelvis oscillatory movement did not exceed 20°. We also observe that when walking straight COM and COP did not oscillate around the same central position; instead COM was displaced more to the left with respect to COP. The same pattern persisted during turning left whereas when turning right asymmetry between COM and COP central positions are diminished. Given the different range of COP movement characteristics in anterior/posterior direction when left or right leg was in stance phase we can also conclude that the left leg was the dominant supporting leg.

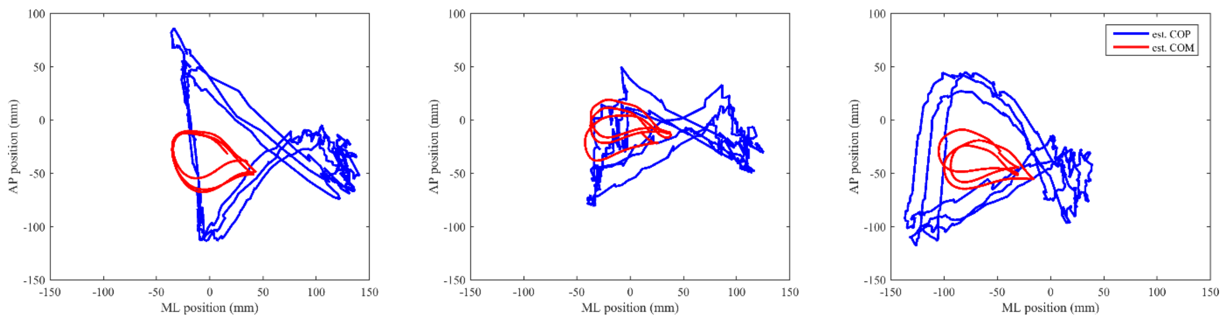


*Figure 14. Stroke subject P1, steady state*

Figure 14 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a case of a stroke patient P1 while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. All three cases display misalignment between COP and COM movement. We observe that when walking straight COM and COP did not oscillate around the same central position but show that COM was displaced more to the left with respect to COP. The same pattern was present during turning left whereas when turning right asymmetry between COM and COP central positions were somewhat less explicit but still evident. We also notice that when the patient was turning (left or right) the majority of bodyweight support was exercised on the left. While to smaller degree the same was true when walking straight.

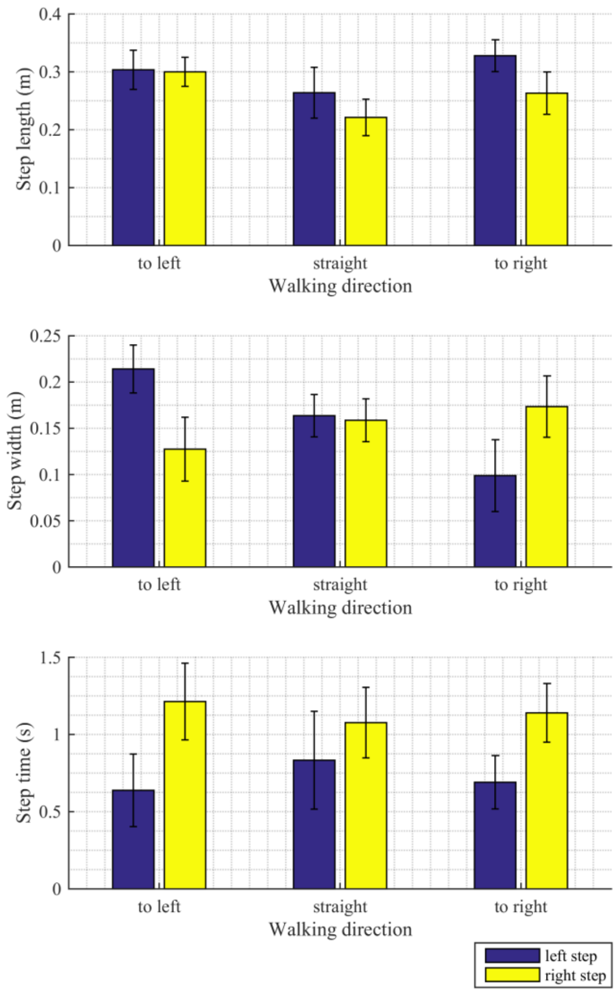


*Figure 15. Stroke subject P1, steady state*

Figure 15 shows step length, step width and step time in a case of a stroke patient P1 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that while left and right step length was almost identical when turning left, left step was longer compared to right step when patient P1 was walking straight or was turning right. Medio/lateral direction was characterized with equal step width when walking straight and wider inner step, i.e. wider left step when turning left and wider right step when turning right. On the other hand regardless whether patient P1 was turning or walking straight right step time was considerably larger.

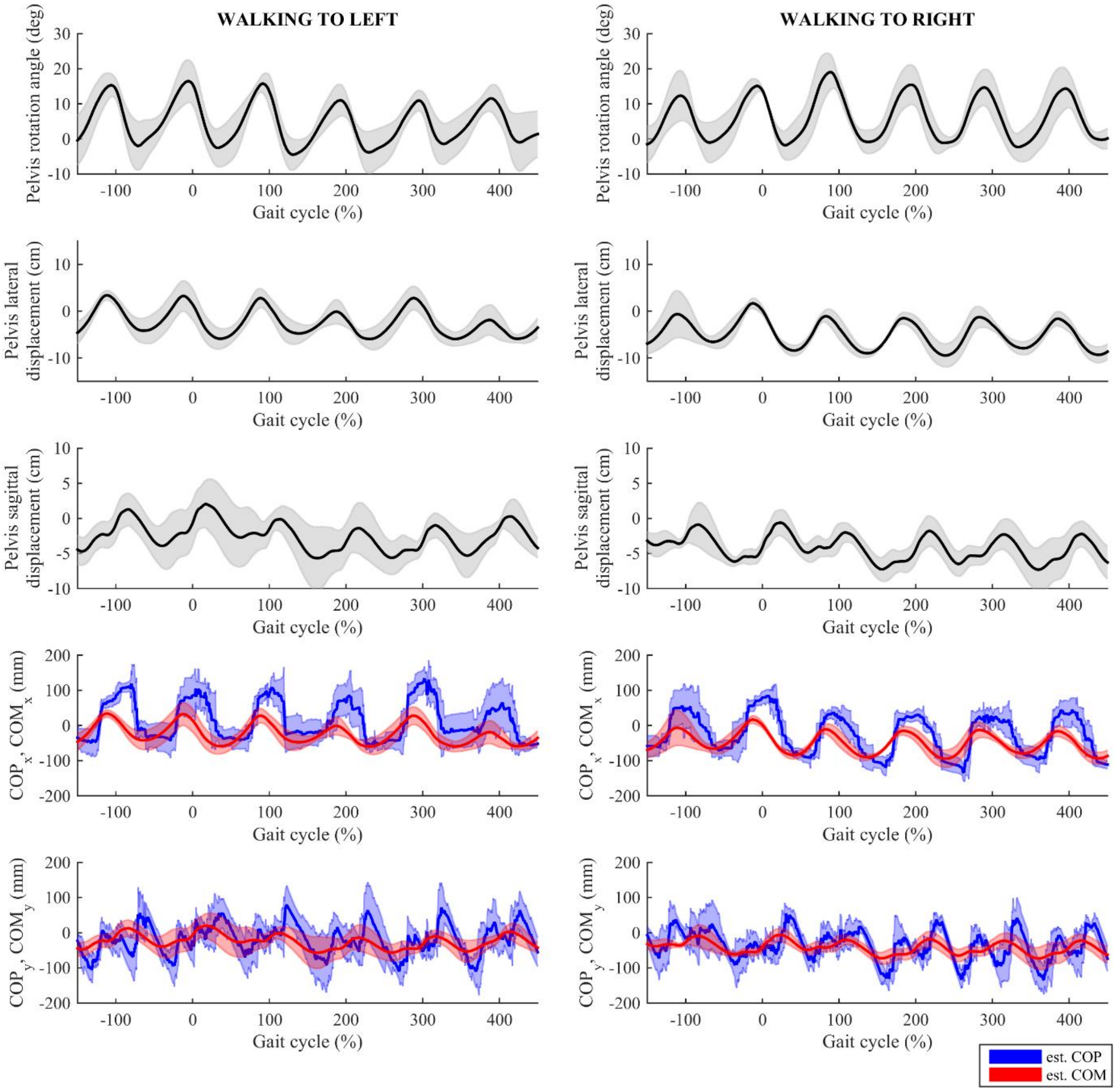


*Figure 161. Stroke subject P1, transients at the beginning of rotation (at 0 %)*

Figure 16 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P1 during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after initiating turning left (left panels) or right (right panels). We notice that the transition did not have consistent effect on pelvis movement. However transition from straight walking to turning was handled differently whether P1 started turning left or right. Namely when patient started turning left COM shifted left with respect to COP whereas when turning right was initiated central position of COM and remained closer to central position of COP in medio lateral direction.

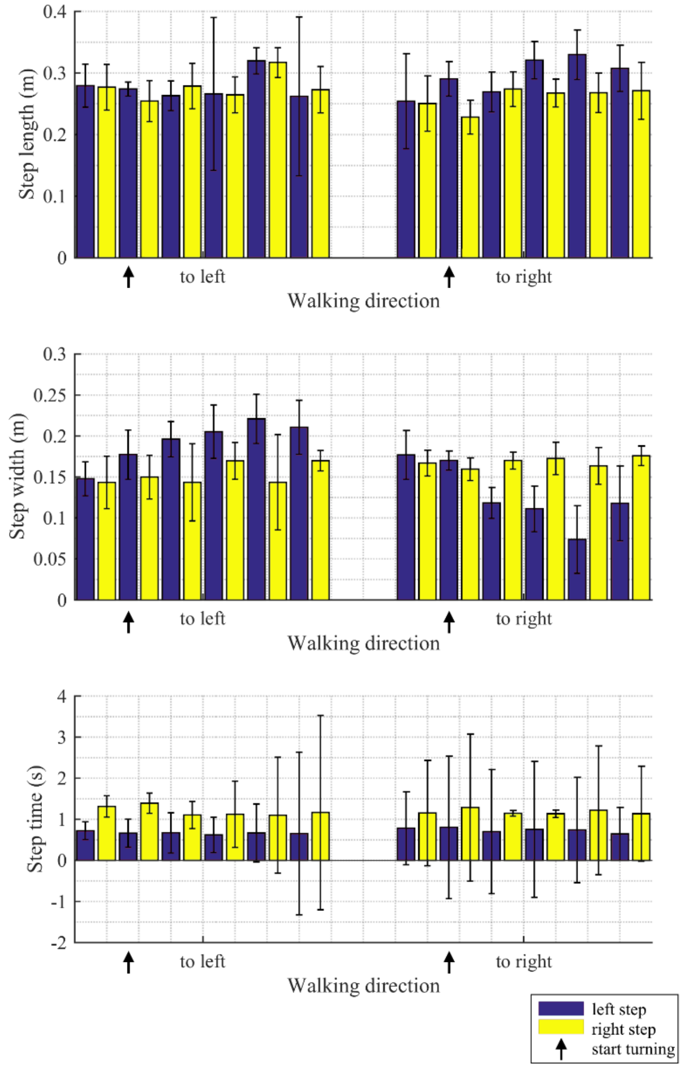


*Figure 17. Stroke subject P1, transients at the beginning of rotation*

Figure 17 shows step lengths, step widths and step times during transition between straight walking and turning left (left panels) or right (right panels) in a case of a stroke patient P1. We observed that initiating turning in left direction did not induce any consistent change between left and right step length. On the other hand after inducing turning in right direction left step length was consistently larger than right step length. Additionally, in both cases the transition had noticeable effect on step width. Transition to turning in left direction increased left step width whereas transition to right increased right step width. In both cases though the transition did not change the asymmetry in step time – right step time remains considerably larger than the left step time.

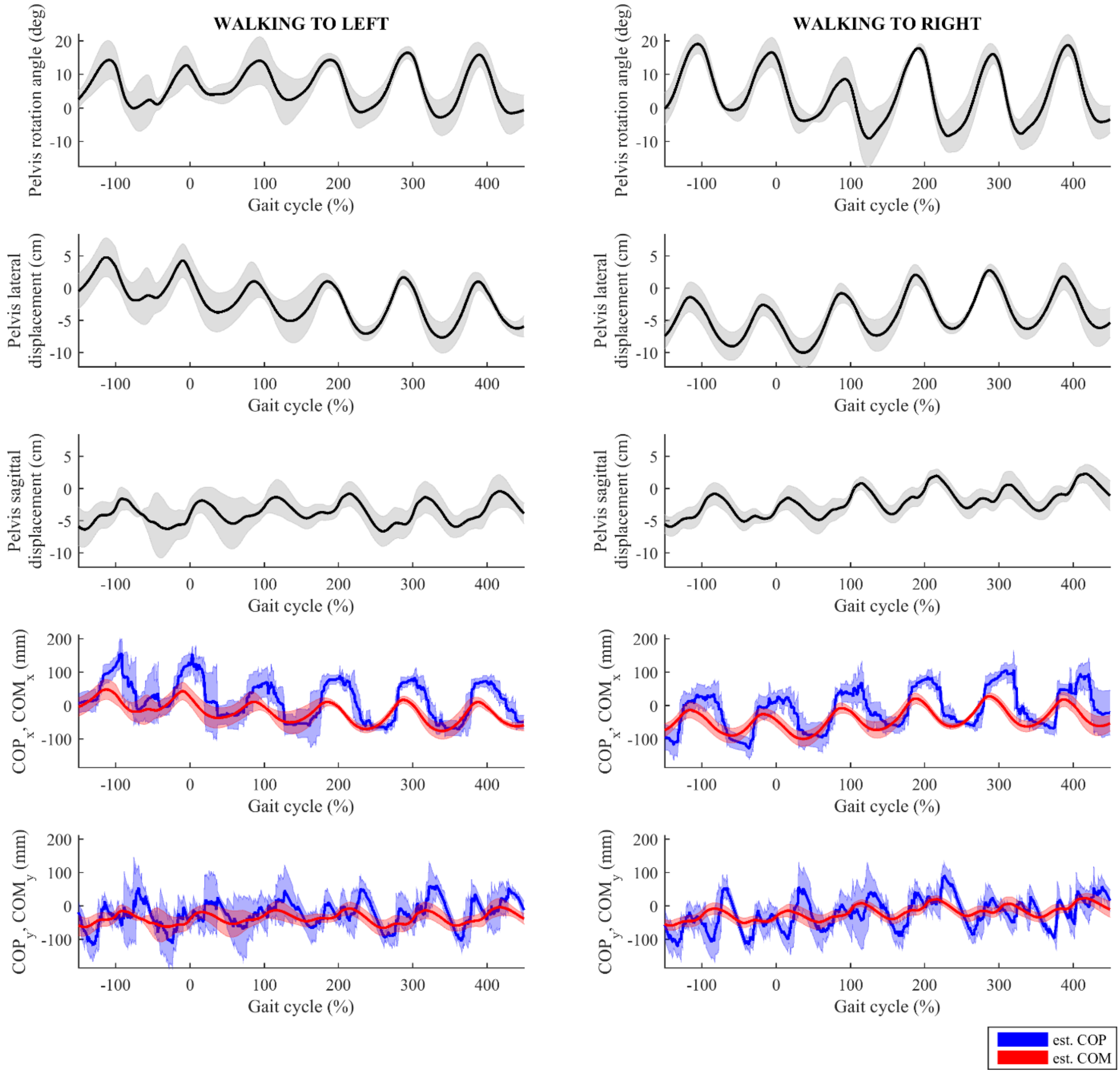


*Figure 18. Stroke subject P1, transients at the end of rotation (at 0 %)*

Figure 18 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P1 during transition between turning left (left panels) or right (right panels) and straight walking - immediately before and after initiating straight walking. We notice that in both cases COP and COM in medio/lateral direction shifted in the same direction as pelvis displacement in medio/lateral direction. We further observe that after transition from turning left to straight walking COM and COP relationship in medio/lateral direction preserved similar asymmetry – COM was displaced more to the left with respect to COP. On the other hand transition from turning right to straight walking was characterized with increasing the asymmetry between the central positions of COM and COP – central positions of COM and COP in medio/lateral direction were in greater alignment before the transition compare to more substantial COM displacement to the left with respect to COP.

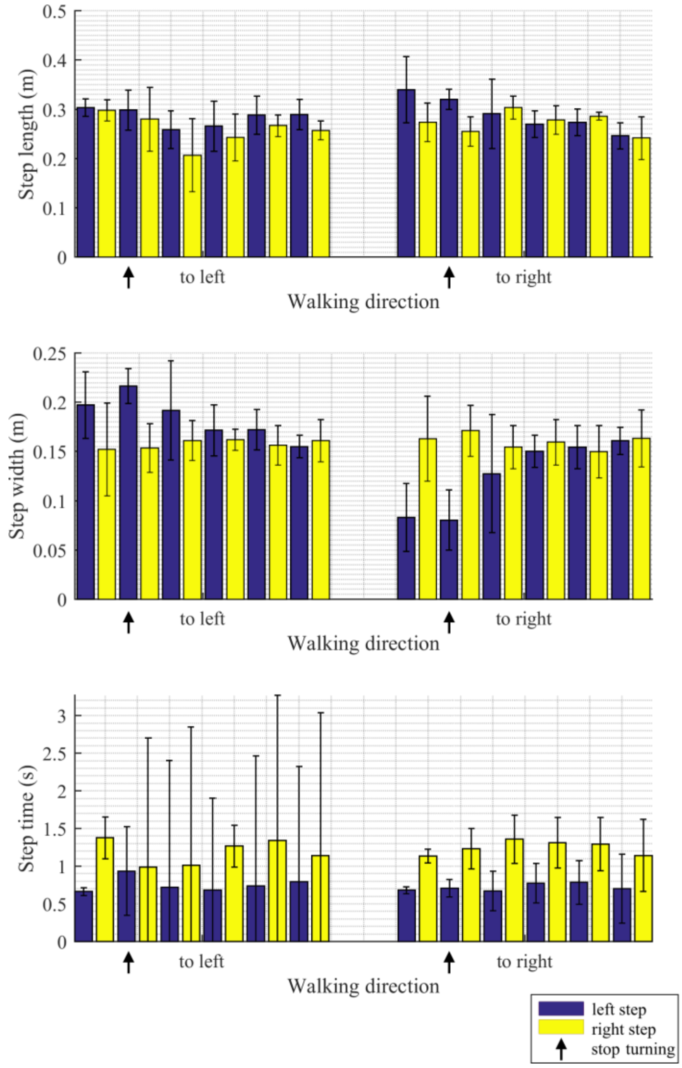


*Figure 19. Stroke subject P1, transients at the end of rotation*

Figure 19 shows step lengths, step widths and step times during transition between walking straight and turning to left (left panels) and right (right panels) - immediately before and after initiating straight walking - in a case of a stroke patient P1. We observe that transition from turning left to straight walking changed approximately symmetrical step length prior to transition to longer left step length after the transition. However, switching from turning in right direction (weaker side) to straight walking improved asymmetrical step length with longer left step length to more symmetrical gait with equal left and right step lengths. In both cases the transition had considerable effect on step width. Transition from turning left to straight walking decreased considerably larger left step width before the transition to almost equal left and right step width. Similar observation was true for transition from turning right to straight walking where larger right step width before the transition was replaced almost equal left and right step width.

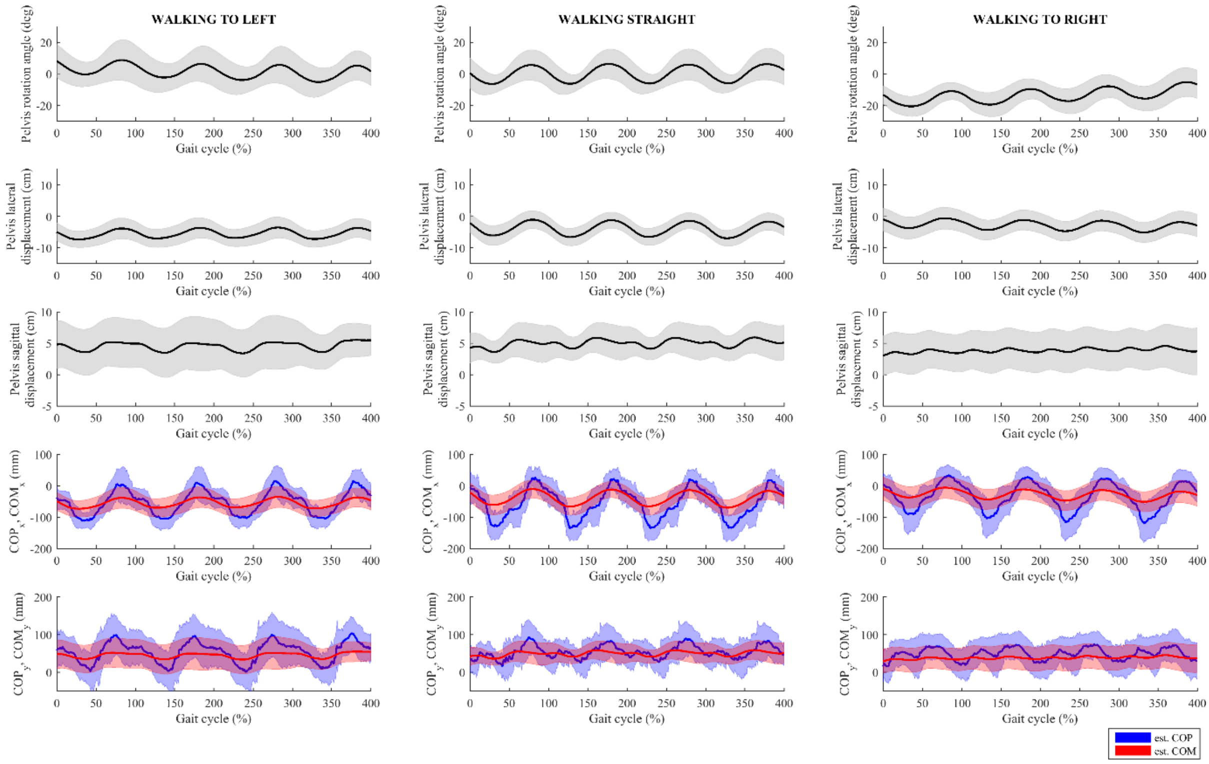


*Figure 20. Stroke subject P2, steady state*

Figure 20 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P2 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that straight walking and turning left was in this subject characterized with pelvis oscillating approximately around neutral rotation in transversal plane, whereas when the patient was turning right pelvis was steadily oscillating in the range between 15° and 20° CW rotation. We also observe that when walking straight COM and COP did not oscillate around the same central position; instead COM was displaced more to the right with respect to COP. The same pattern persisted during turning right whereas when turning left asymmetry between COM and COP central positions were diminished and central positions of COM and COP were approximately aligned. Given the different range of COP movement characteristics in anterior/posterior direction when left or right leg was in stance phase – the range of COP movement when right leg was supporting leg was larger compared to when the left leg was supporting leg - we can also conclude that the right leg was the dominant supporting leg.

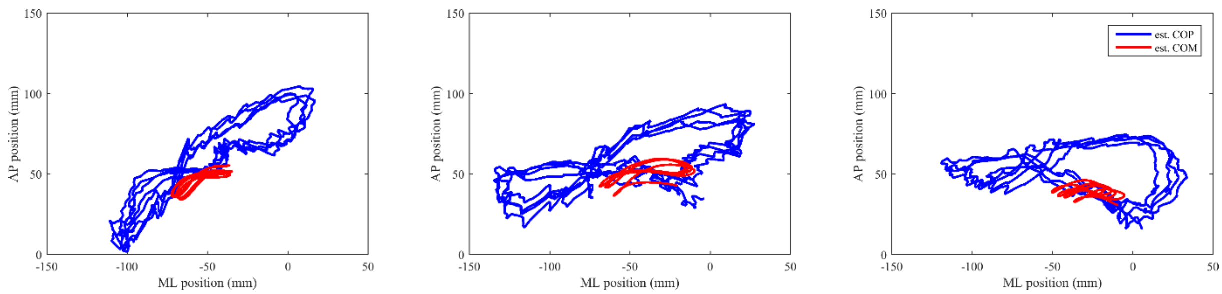


*Figure 21. Stroke subject P2, steady state*

Figure 21 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a case of a stroke patient P2 while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. We observe that when walking straight COM and COP did not oscillate around the same central position but show that COM was displaced more to the right with respect to COP. The same pattern was present during turning right whereas when turning left asymmetry between COM and COP central positions were diminished and central positions of COM and COP were approximately aligned. We also notice that when the patient was turning (left or right) the majority of bodyweight support was exercised on the right side. While to lesser degree the same was true when walking straight. We also notice that in particular when walking straight and turning right the range of COP movement was more pronounced when right leg was the supporting leg which indicates that the right leg was the dominant supporting leg.

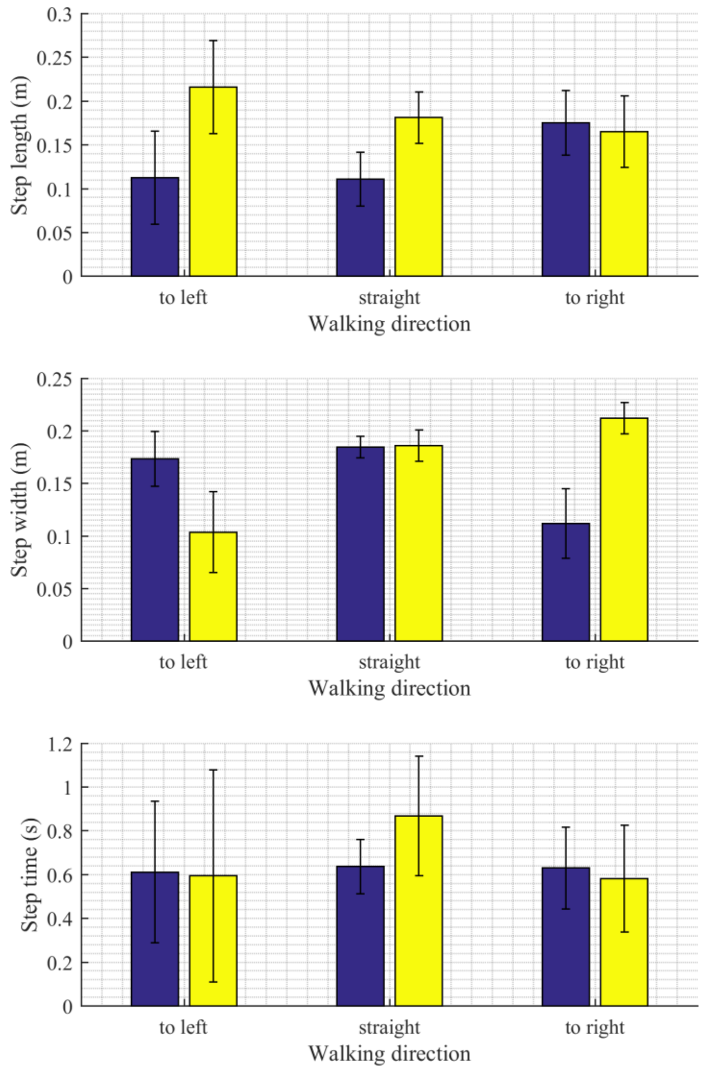


*Figure 22. Stroke subject P2, steady state*

Figure 22 shows step length, step width and step time in a case of a stroke patient P2 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that while left and right step lengths were almost identical when turning right, right step was considerably larger when compared to left step when patient P2 was walking straight or was turning left. Medio/lateral direction was characterized with equal step width when walking straight and wider inner step, i.e. wider left step when turning left and wider right step when turning right. On the other hand regardless whether patient P2 was turning left or right, left and right step times were approximately equal whereas when walking straight right step time was considerably larger compared to left step time.

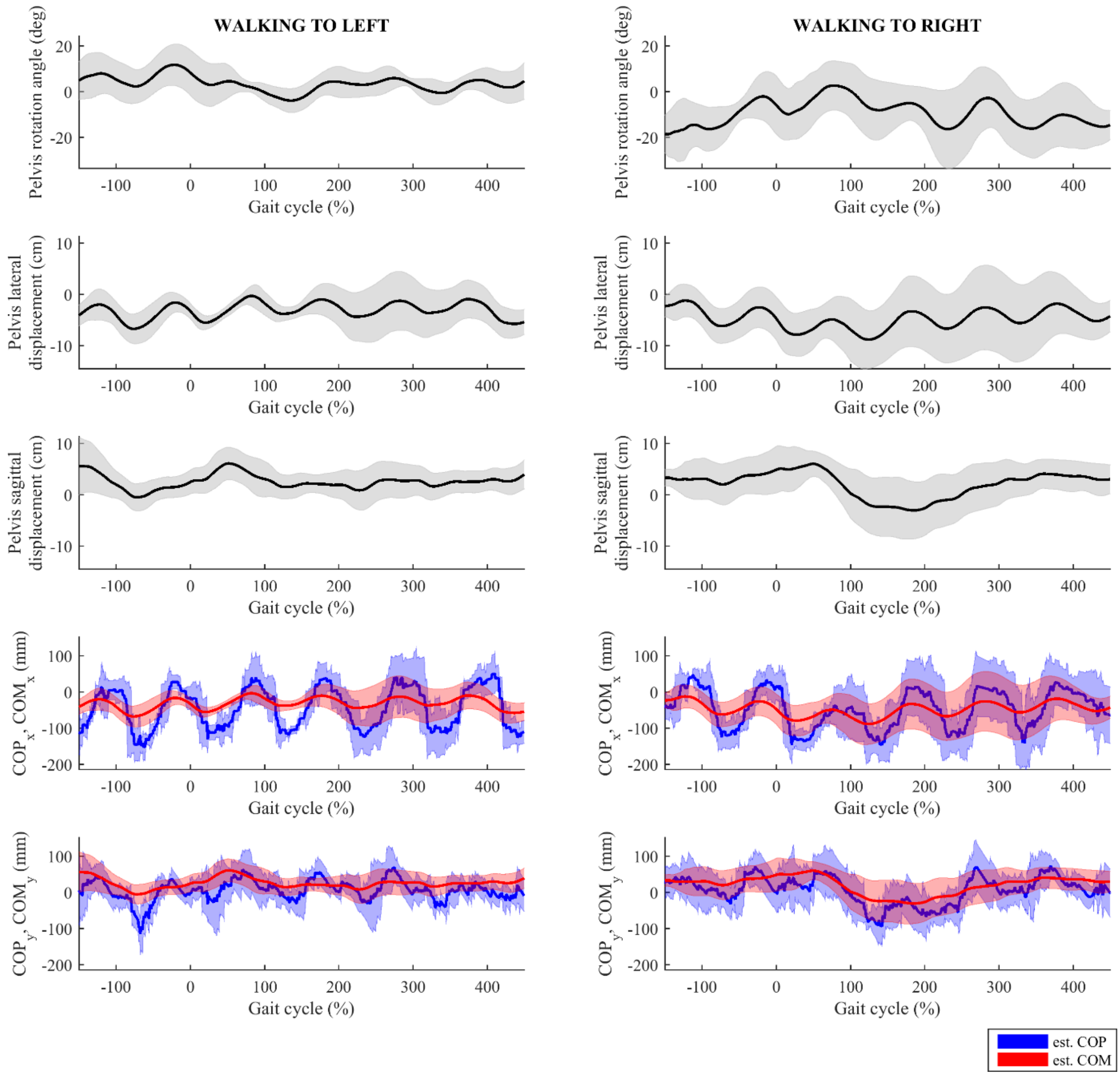


*Figure 23. Stroke subject P2, transients at the beginning of rotation (at 0 %)*

Figure 23 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P2 during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after initiating turning left (left panels) or right (right panels). We notice that both transitions caused larger variability in pelvis movement in transversal plane. The most noticeable effect on pelvis movement was evident after transition from walking straight to turning in right direction where the transition was accompanied with short pelvis displacement in left direction and fast recovery to approximately the same position as prior to transition onset. This also reflected in temporary COM displacement to the left immediately after the transition. We also observe that when initiating turning in right direction to large extent did not change relationship between COM and COM in medio/lateral direction – central position of COM movement remained slightly displaced to the right with respect to COP. On the other hand after turning to the left was initiated the misalignment in central position of COM and COP diminished to the extent that both central positions of COM and COP were almost aligned.

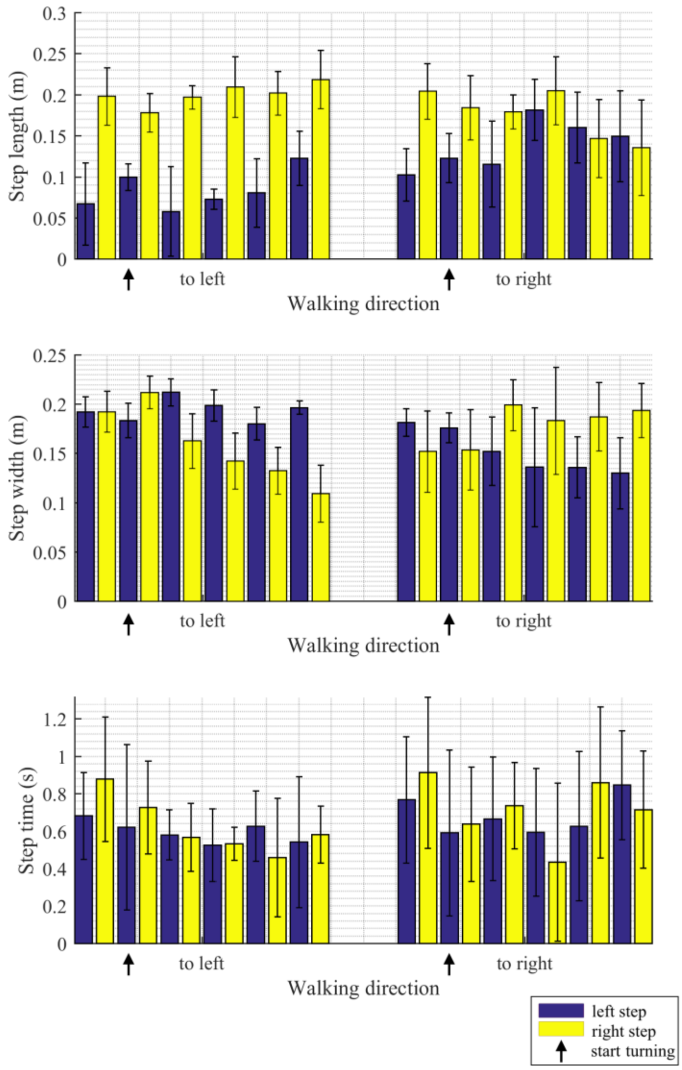


*Figure 24. Stroke subject P2, transients at the beginning of rotation*

Figure 24 shows step lengths, step widths and step times during transition between straight walking and turning left (left panels) or right (right panels) in a case of a stroke patient P2. We observe that initiating turning in left direction did not have effect on left and right step length relationship – after the transition right step remained considerably longer. On the other hand when initiating the transition between straight walking and turning in right direction step length asymmetry improved to the extent that left and right step lengths were approximately equal. Additionally, in both cases the transition had noticeable effect on step width. Transition to turning in left direction increased left step width whereas transition to right increased right step width. Somewhat less consistent effects of transitions were present in step times. When turning left was initiated longer left step times settled at similar left and right step time.

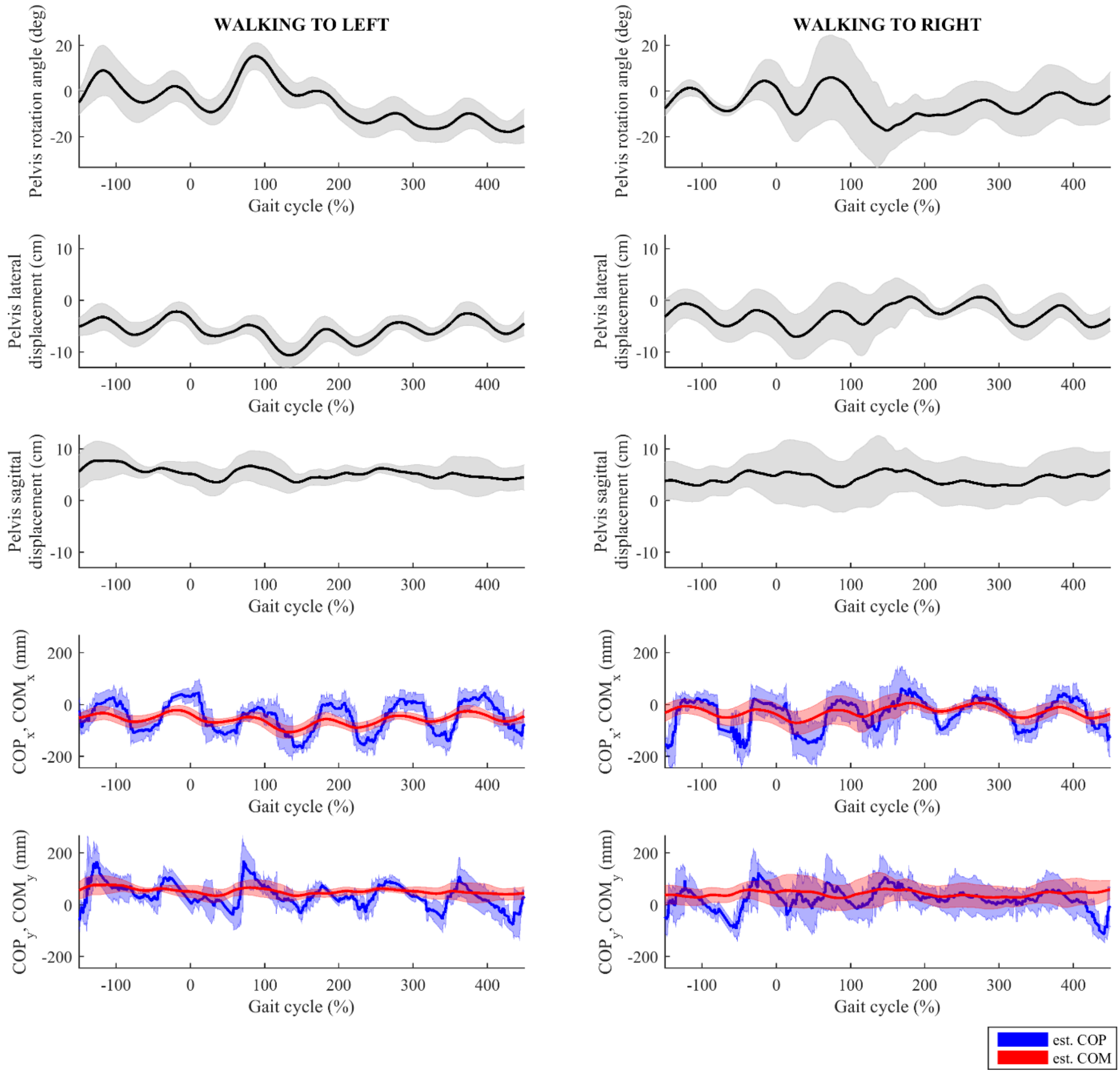


*Figure 25. Stroke subject P2, transients at the end of rotation (at 0 %)*

Figure 25 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P2 during transition between turning left (left panels) or right (right panels) and straight walking - immediately before and after initiating straight walking. Increased standard deviation of pelvis movement in the stride immediately after transition between turning right and walking straight shows that the transition temporarily induced somewhat more variable pelvis movement. We also notice that after turning in right direction ended the relationship between COM and COP did not change considerably and COM remained shifted more to the right with respect to COP. Somewhat different response was observed after transition from turning in left direction to straight walking where approximately aligned central positions of COM and COP before the transition persisted after the transition although tendency begins to appear where central position of COM gradually shifted more to the right with respect to COP.

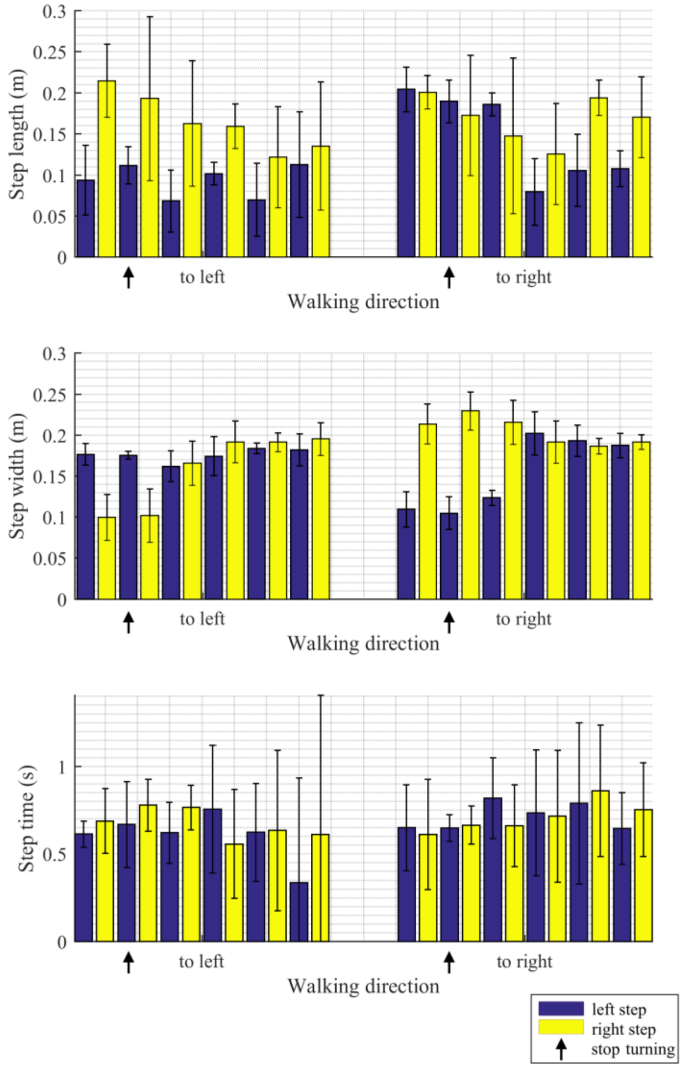


*Figure 26. Stroke subject P2, transients at the end of rotation*

Figure 26 shows step lengths, step widths and step times during transition between walking straight and turning to left (left panels) and right (right panels) - immediately before and after initiating straight walking - in a case of a stroke patient P2. We observe that after transition from turning left to straight walking large asymmetry in step length was gradually reduced but was nonetheless was present after perturbation – right step was longer compared to left step. On the other hand transition from turning in right direction was characterized with larger step length symmetry before the transition and considerably larger right step after the transition. In both cases the transition had considerable effect on step width. Transition from turning left to straight walking decreased considerably larger left step width before the transition to almost equal left and right step widths. Similar observation was true for transition from turning right to straight walking where larger right step width before the transition was replaced with almost equal left and right step widths.

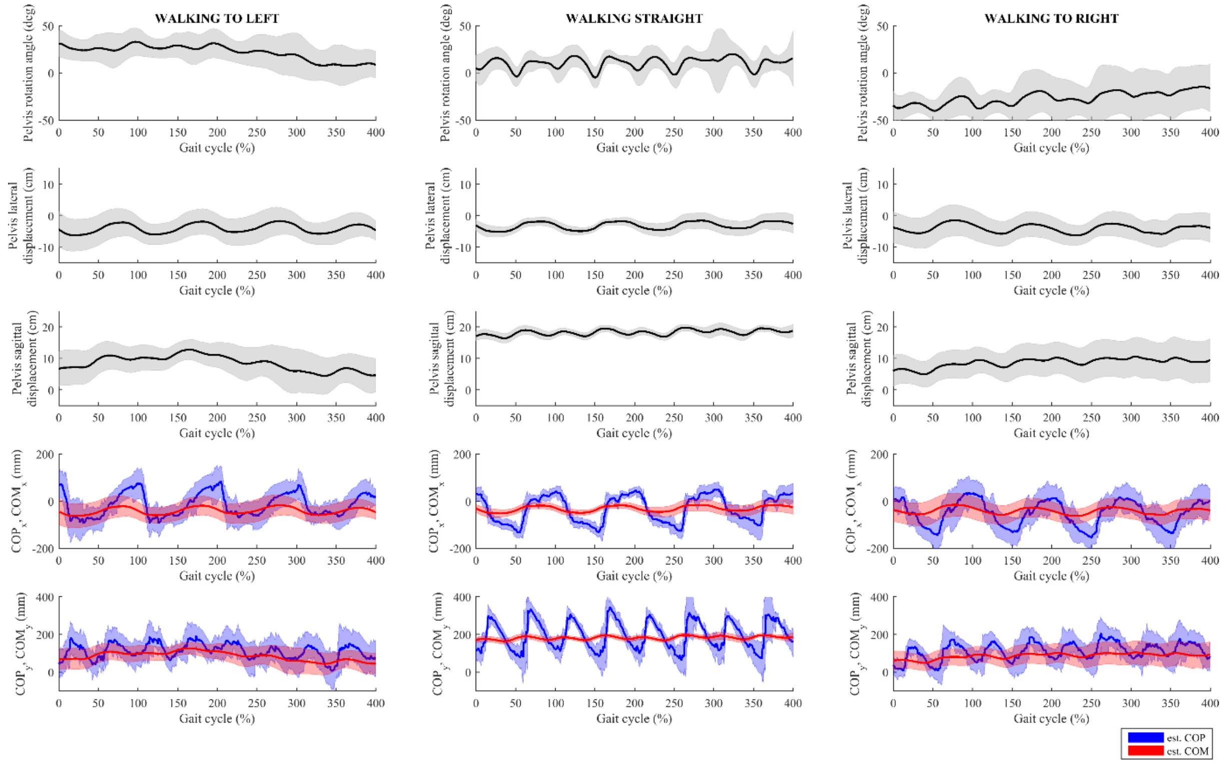


*Figure 27. Stroke subject P3, steady state*

Figure 27 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P3 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that during straight walking pelvis rotation in transversal plane oscillated close to neutral position whereas when turning left and right pelvis rotation was characterized with considerable CCW and CW rotations respectively. When walking straight we also notice minor displacement of central COM movement to the right with respect to central COP movement. When the patient was turning right central position of COM shifted even further to the right with respect to central position of COP whereas when the patient was turning left central position of COM shifted left with respect to central position of COP. Comparing the range of COP movement in medio/lateral and anterior/posterior direction further indicated that the range of support decreases when the subject was turning. In general larger standard deviations of results when the patient was turning also suggest higher variability during turning.

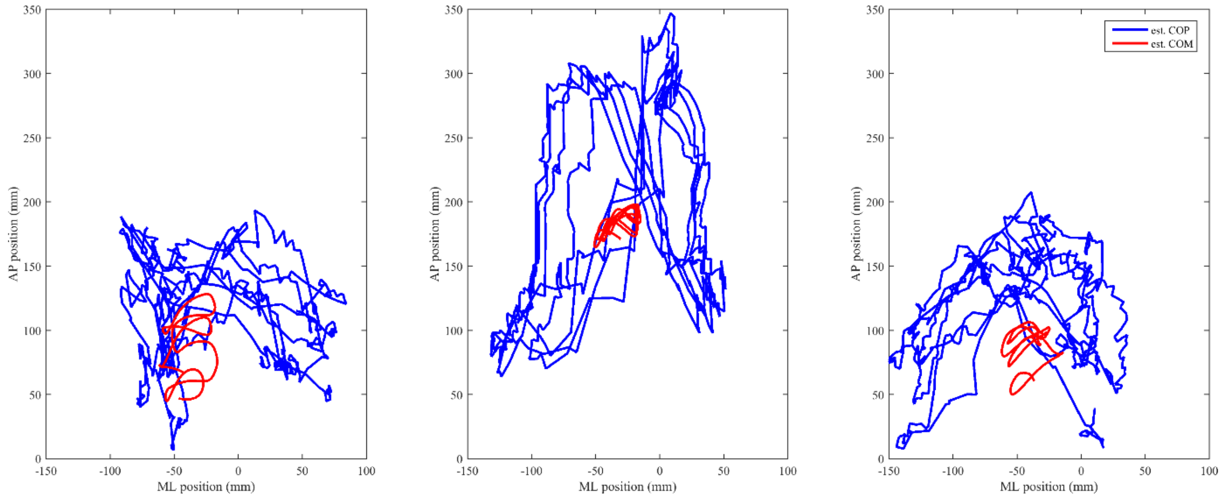


*Figure 28. Stroke subject P3, steady state*

Figure 28 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a case of a stroke patient P3 while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. We notice minor displacement of central COM movement to the right with respect to central COP movement during straight walking. When the patient was turning right central position of COM shifted even further to the left with respect to central position of COP whereas when the patient was turning left central position of COM shifted left with respect to central position of COP. Comparing the range of COP movement in medio/lateral and anterior/posterior direction further indicates that the range of support decreased when the subject was turning. We also observe that both cases of turning displayed larger variability in COM as well as COP movement with somewhat less consistent pattern compared to straight walking.

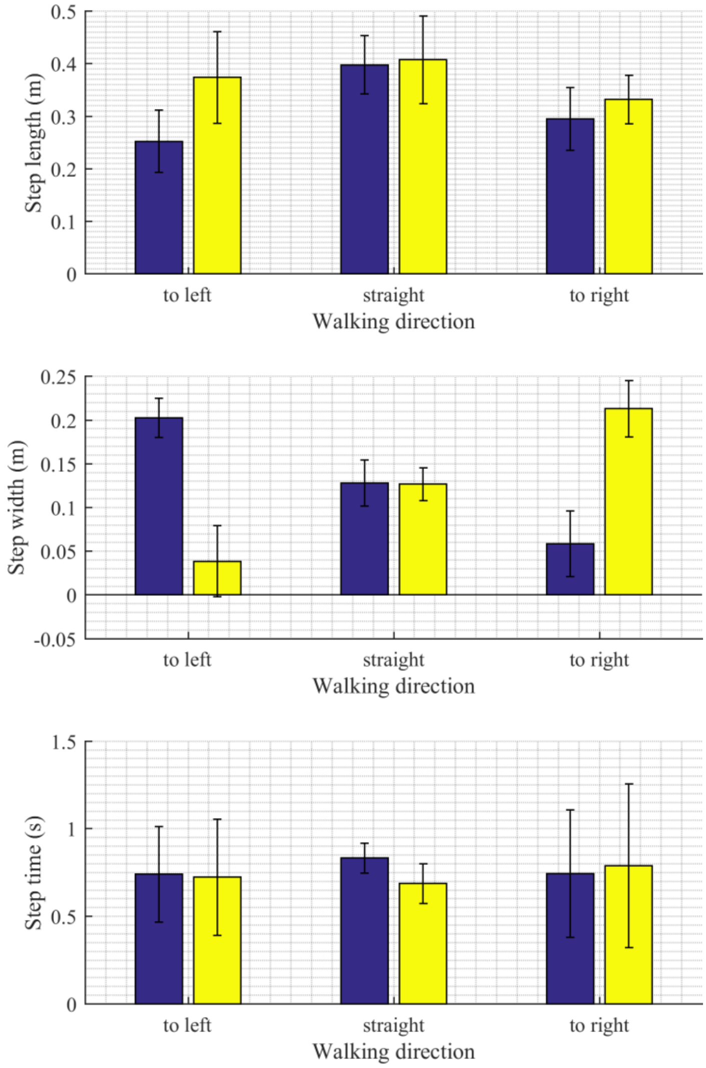


*Figure 29. Stroke subject P3, steady state*

Figure 29 shows step length, step width and step time in a case of a stroke patient P3 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that while left and right step lengths were almost the same when walking straight, whenever the patient was turning right step was longer than left step but both left and right steps were shorter compared to straight walking. Medio/lateral direction was characterized with equal step width when walking straight and wider inner step, i.e. wider left step when turning left and wider right step when turning right. On the other hand regardless whether the patient was turning left or right left or was walking straight step times were in all cases approximately equal.

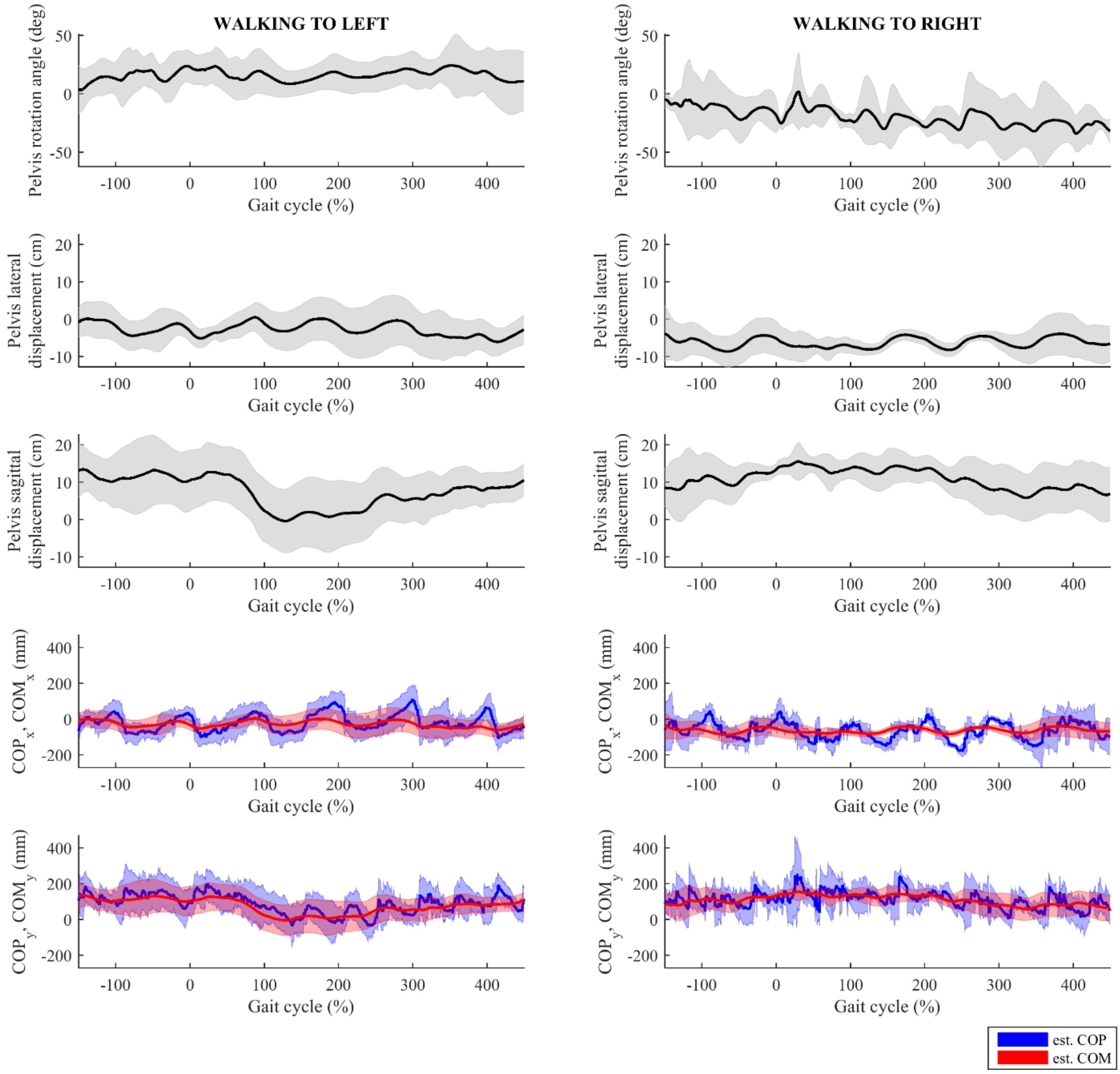


*Figure 30. Stroke subject P3, transients at the beginning of rotation (at 0 %)*

Figure 30 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P3 during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after initiating turning left (left panels) or right (right panels). We notice that transitions caused very subtle changes that resulted in temporary pelvis displacement in medio/lateral direction and corresponding displacement of COM and COP in the same direction. Also, there was a tendency present to increase pelvis rotation in the direction opposite to the direction of turning, i.e. CW pelvis rotation after initiating turning left and CCW pelvis rotation after initiating turning right. Similarly, the relationship between COM and COP shows that in both cases of transition central positions of COM movement was somewhat displaced with respect to COP in the direction of turning. In general in this patient changes are subtle and show less consistency.

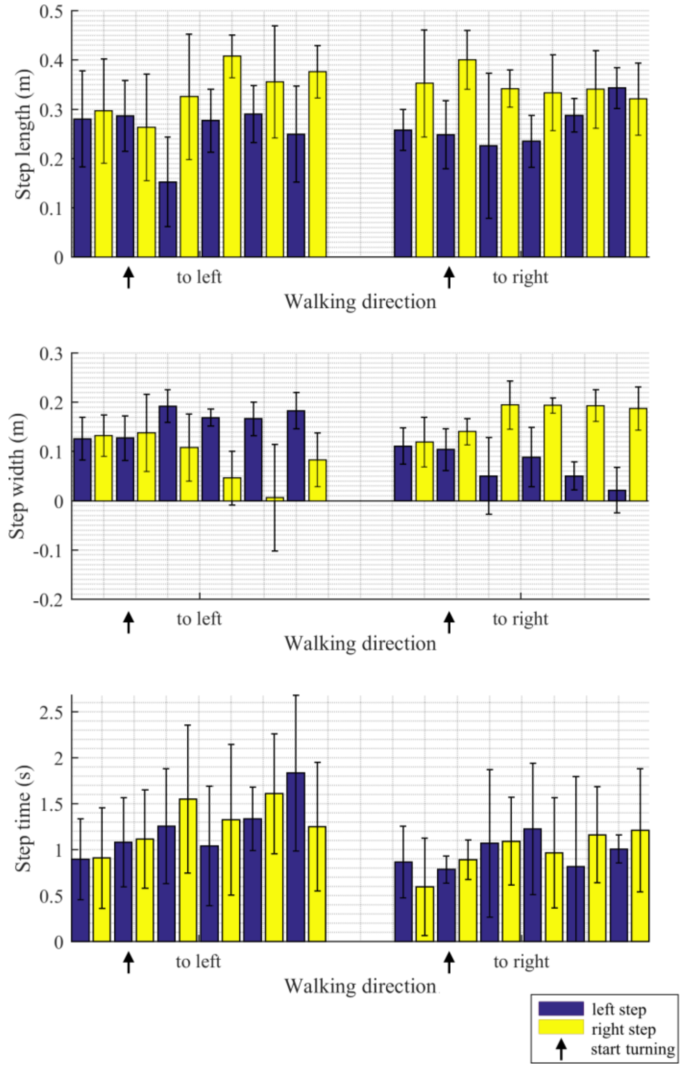


*Figure 31. Stroke subject P3, transients at the beginning of rotation*

Figure 31 shows step lengths, step widths and step times during transition between straight walking and turning left (left panels) or right (right panels) in a case of a stroke patient P3. We observe that initiating turning in left direction results in considerably increasing right step length compared to left step length. When initiating turning in other direction right steps were longer in first three strides whereas afterwards symmetry in step length improved to the extent that left and right step lengths were similar. Additionally, in both cases the transition had noticeable effect on step width. Transition to turning in left direction increased left step width whereas transition to right increased right step width. Somewhat less evident was the effect of transitions on step times where no consistent pattern could be recognized.

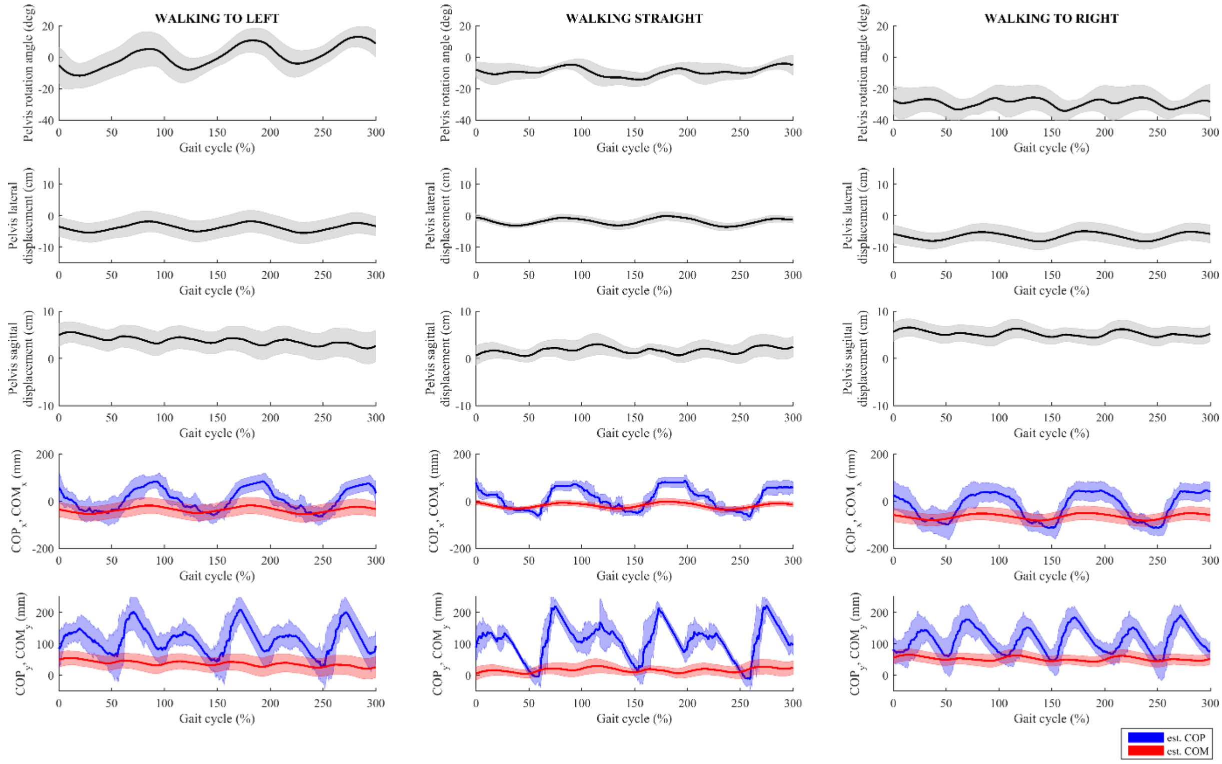


*Figure 32. Stroke subject P4, steady state*

Figure 32 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P4 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that compared to straight walking pelvis rotation in transversal plane was in pronounced CCW rotation when turning left and pronounced CW rotation when turning right. We also notice that the patient was very consistent in displacing COM to the left and backward with respect to COP in all three cases.

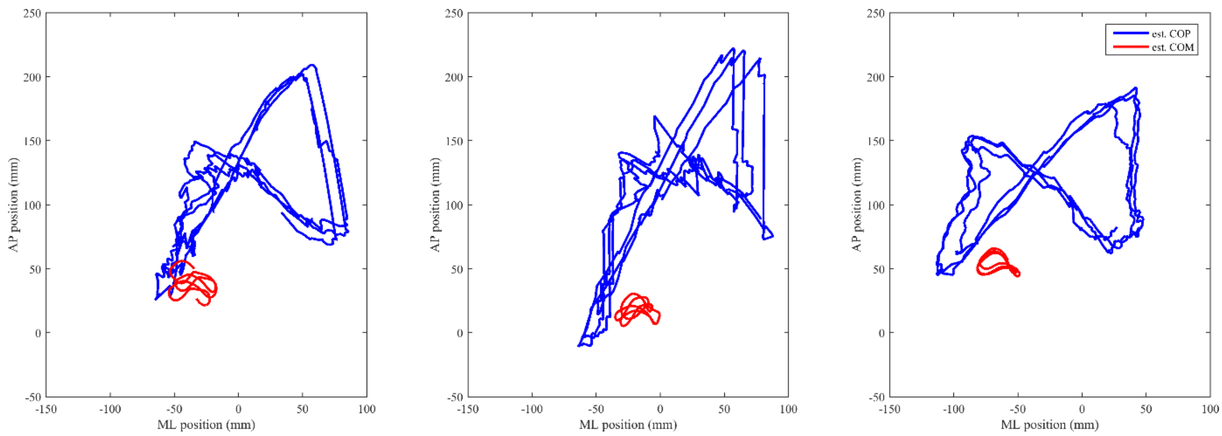


*Figure 33. Stroke subject P4, steady state*

Figure 33 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a case of a stroke patient P4 while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. We observe that in all three cases the patient was displacing COM to the left and backward with respect to COP.

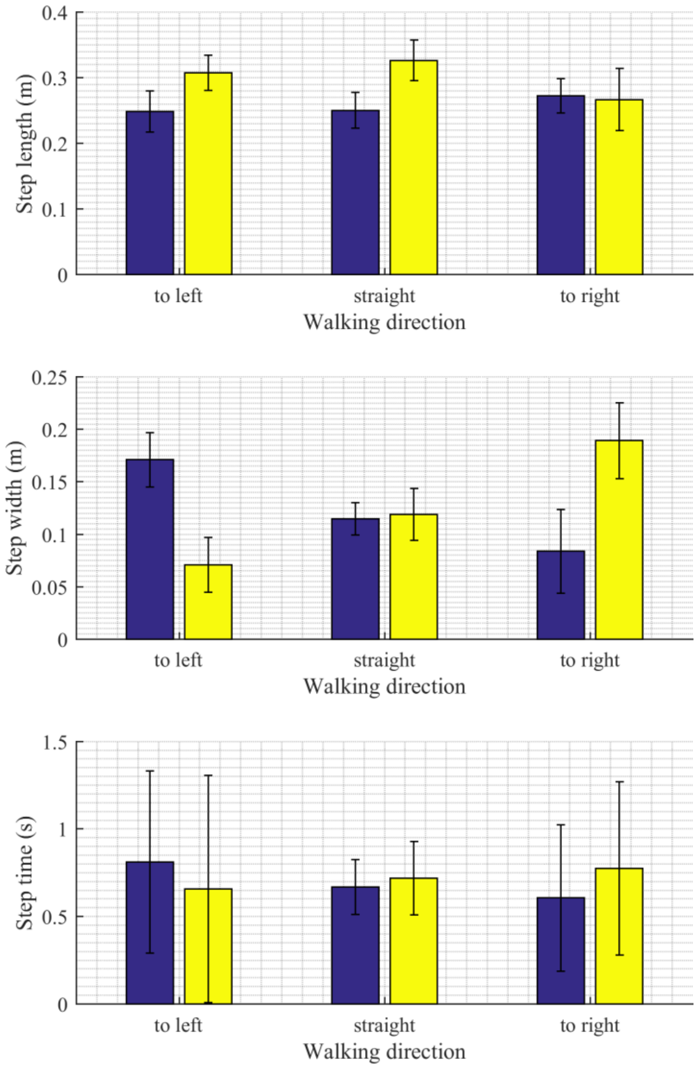


*Figure 34. Stroke subject P4 (Oberstar), steady state*

Figure 34 shows step length, step width and step time in a case of a stroke patient P4 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that when the patient was walking straight or was turning left right step was longer than left step. On the other hand both steps were approximately equal in length when the patient was turning right. Medio/lateral direction is characterized with equal step width when walking straight and wider inner step, i.e. wider left step when turning left and wider right step when turning right. Similar characteristics were present in step time results where left and right step times were similar during straight walking, left step time was larger during turning left but when turning in right direction right step time was larger compared to left step time.

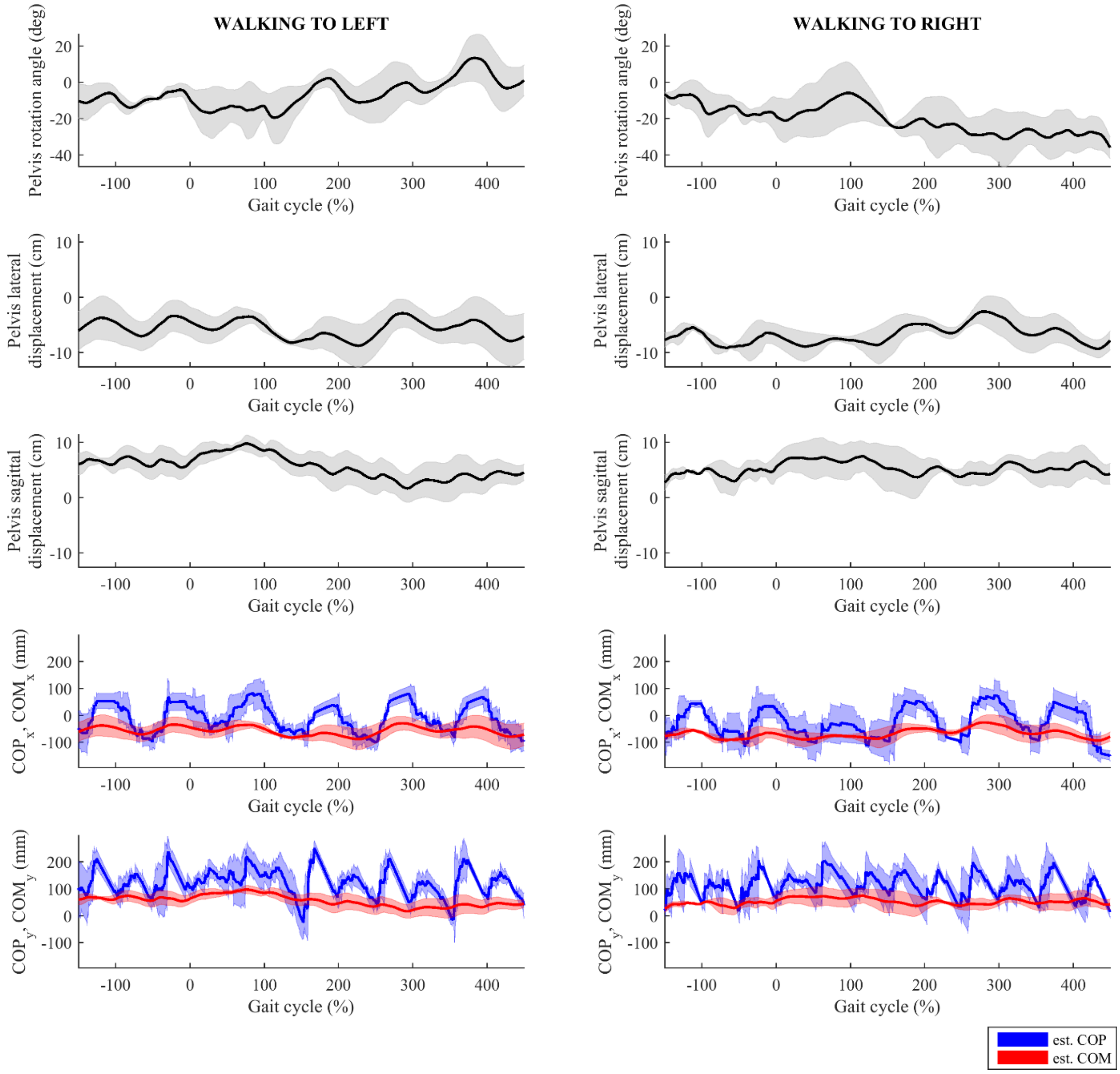


*Figure 35. Stroke subject P4, transients at the beginning of rotation (at 0 %)*

Figure 35 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P4 during transition between walking straight and turning left (left panels) or right (right panels) - immediately before and after initiating turning left (left panels) or right (right panels). We notice that both transitions increased pelvis rotation in the direction of turning, i.e. CCW when initiating turning to left and CW when initiating turning to right. On the other hand transition did not have noticeable effect on the relationship between COM and COP. In both cases central position of COM remained displaced toward left with respect to COP regardless of transition type.

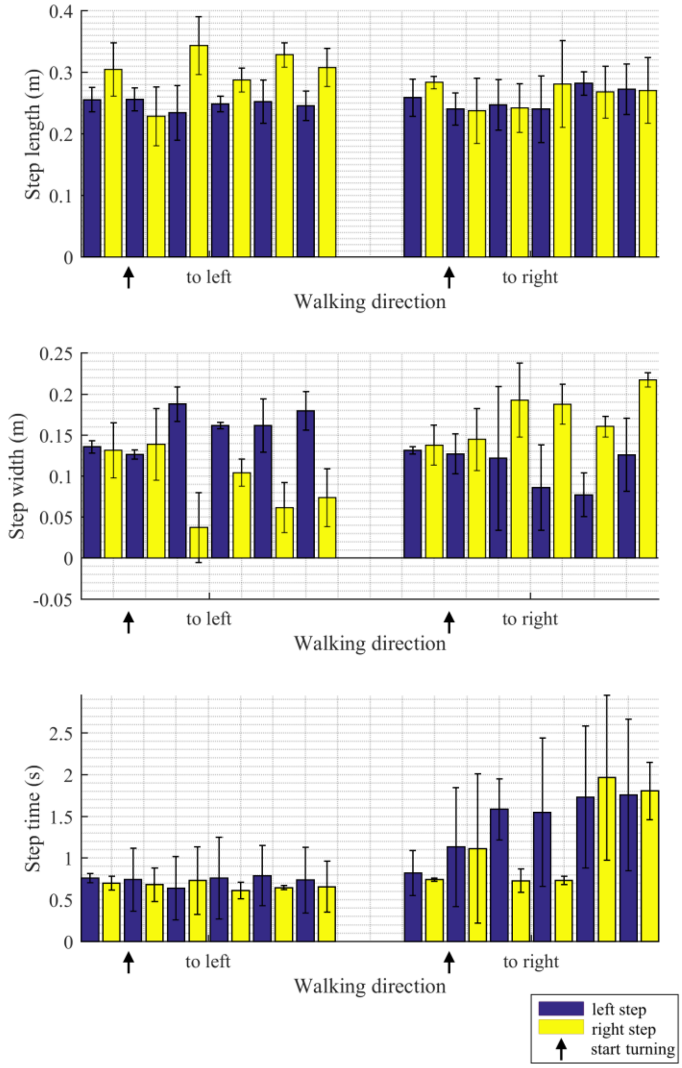


*Figure 36. Stroke subject P4, transients at the beginning of rotation*

Figure 36 shows step lengths, step widths and step times during transition between straight walking and turning left (left panels) or right (right panels) in a case of a stroke patient P4. We observe that initiating turning in left direction first temporarily equaled left and right step length and then induced similar step length asymmetry as before the transition, i.e. right step was longer compared to left step. On the other hand after inducing turning in right direction asymmetry that was characterized with longer right step improved to the extent where left and right steps were approximately equal. Additionally, in both cases the transition had noticeable effect on step width. Transition to turning in left direction increased left step width whereas transition to right increased right step width. Somewhat less evident was the effect of transitions on step times. After initiating turning in left direction we did not observe considerable changes in step times although minor tendency to increase left step time was present. Larger effect was present after initiating turning to right where left step time temporarily increased in three strides after the transition but approximately equalized in the next stride.

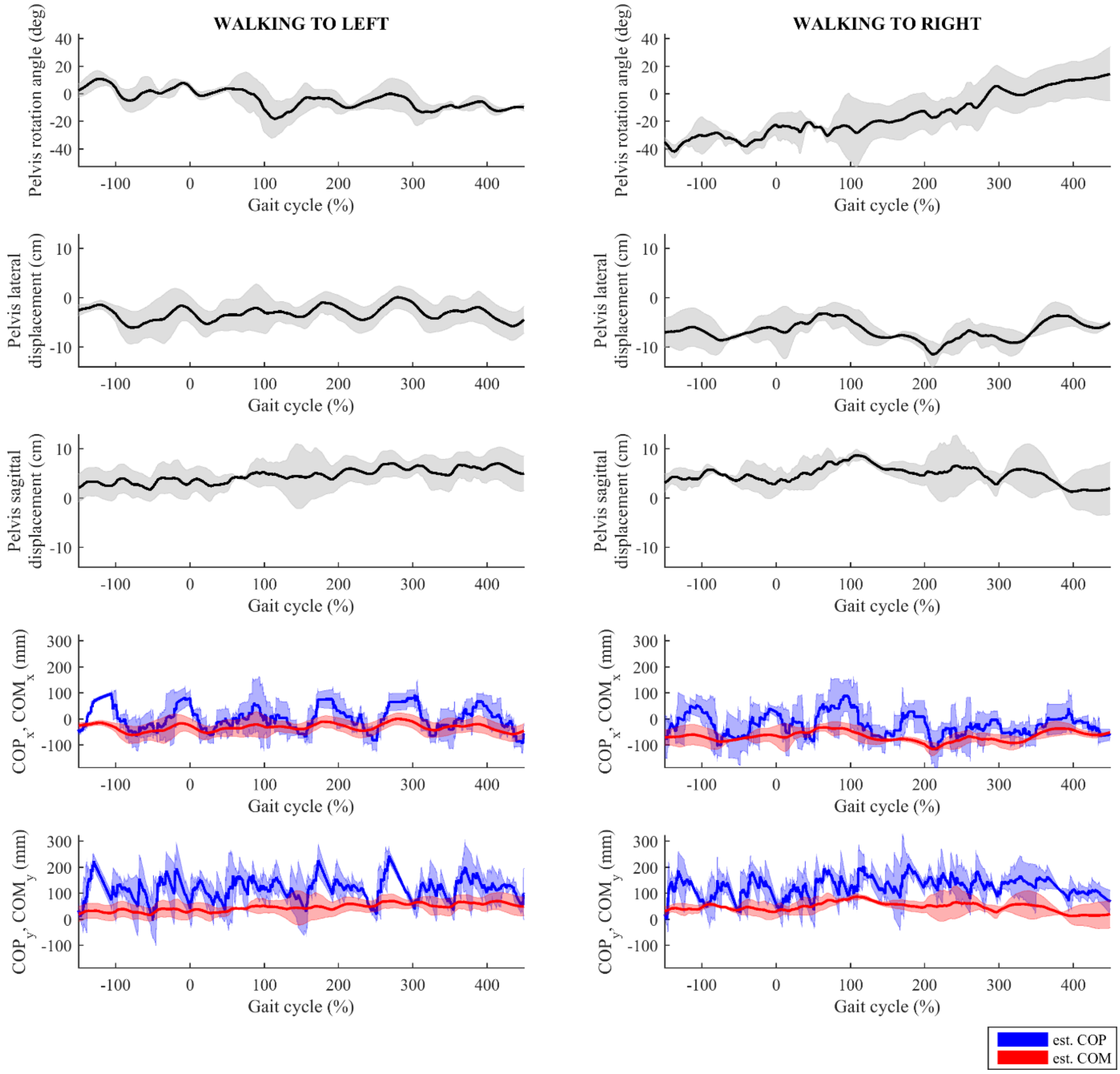


*Figure 37. Stroke subject P4, transients at the end of rotation (at 0 %)*

Figure 37 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P4 during transition between turning left (left panels) or right (right panels) and straight walking - immediately before and after initiating straight walking. We notice that both transitions were characterized with pelvis rotation in transversal plane being diminished – transition from turning in left direction to straight walking induced mild but sustainable decrease of CCW pelvis rotation whereas transition from turning in right direction to straight walking induced pronounced and sustainable decrease of CW pelvis rotation toward neutral position. However transitions did not have considerable effect on the relationship between COM and COP. In both cases we recoded left and backward displacement of COM with respect to COP.

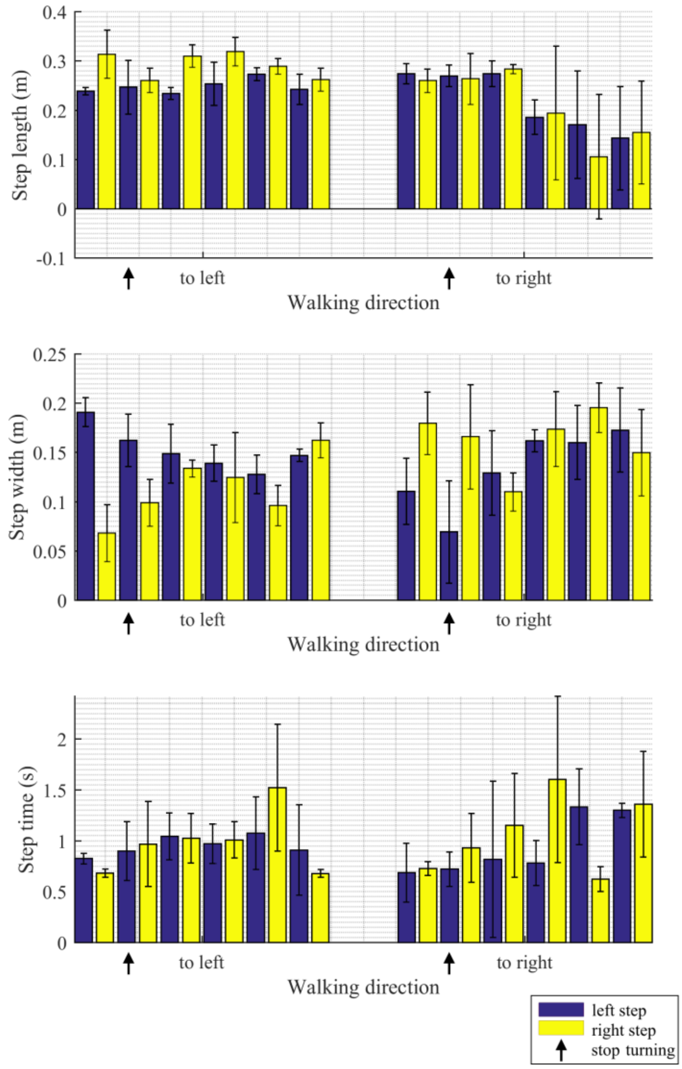


*Figure 38. Stroke subject P4, transients at the end of rotation*

Figure 38 shows step lengths, step widths and step times during transition between walking straight and turning to left (left panels) and right (right panels) - immediately before and after initiating straight walking - in a case of a stroke patient P4. We observe that after transition from turning left to straight walking asymmetry in step length where right step was longer than left step persisted also after transition. On the other hand transition from turning in right direction was characterized with shorter left and right steps with no consistent step length pattern being developed shortly after the transition. In both cases the transition had considerable effect on step width. Transition from turning left to straight walking decreased considerably larger left step width before the transition and induced more symmetrical left and right step width after the transition. Similar observation was true for transition from turning right to straight walking where larger right step width before the transition was replaced with more symmetrical left and right step width. In addition, transitions introduced inconsistencies in step times but no consistent step time pattern developed in neither case.

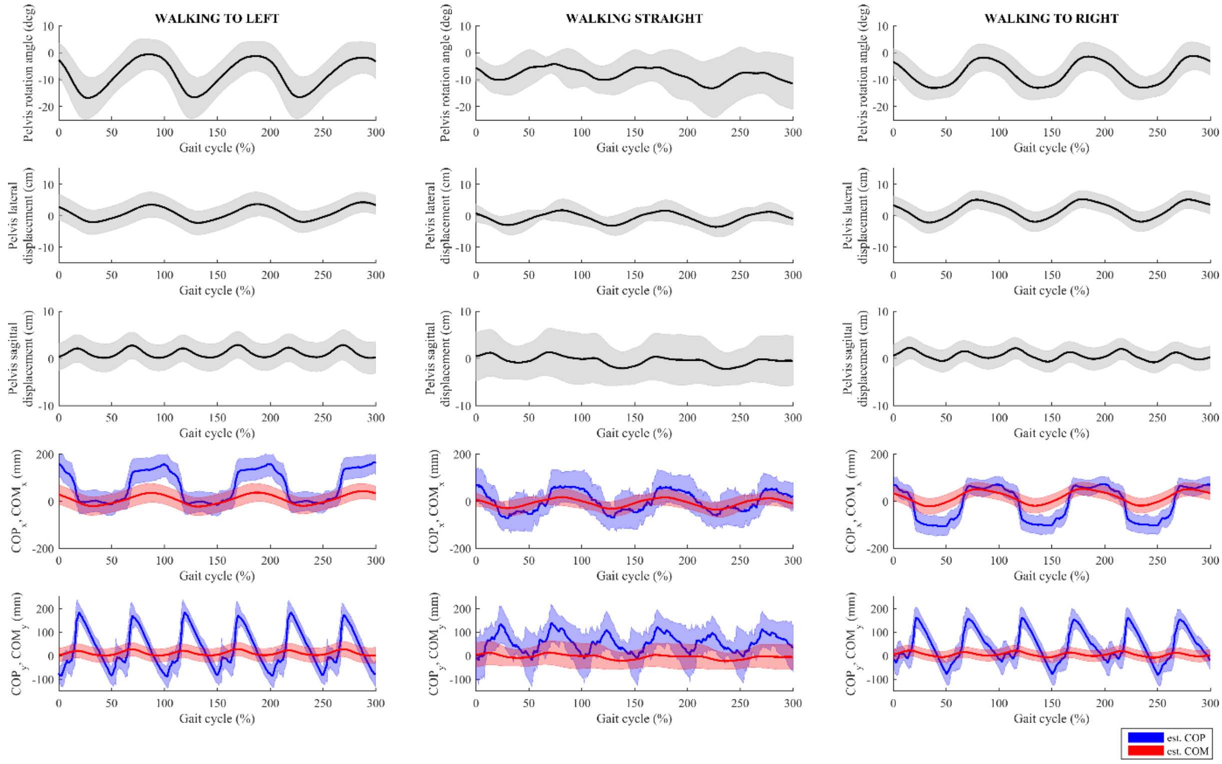


*Figure 39. Stroke subject P5, steady state*

Figure 39 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) as well as movement of COP and COM in anterior/posterior and medio/lateral direction in a case of a stroke patient P5 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We notice that in all three cases pelvis exhibited very similar movement in transversal plane. More notable differences existed in relationship between COM and COP. When walking straight COP and COM in medio/lateral direction oscillated around the same central position whereas when turning COM shifted with respect to COP in the direction of turning (inward), i.e. when turning left COM shifted more to the left with respect to COP and it shifted more to the right with respect to COP when turning right.

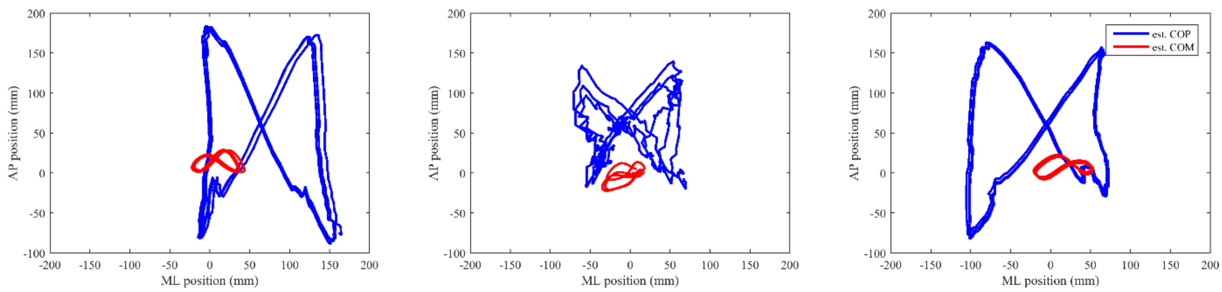


*Figure 40. Stroke subject P5, steady state*

Figure 40 shows a phase diagram of COM and COP movement in medio/lateral and anterior/posterior direction in a case of a stroke patient P5 while continuously turning left (left), walking straight (middle) and continuously turning right (right). It displays graphically the relationship between movement of COM and COP in three selected cases. When walking straight center of COM movement and center of COP movement in medio/lateral direction were approximately aligned whereas when turning COM shifted with respect to COP in the direction of turning (inward), i.e. when turning left COM shifted more to the left with respect to COP and it shifted more to the right with respect to COP when turning right.

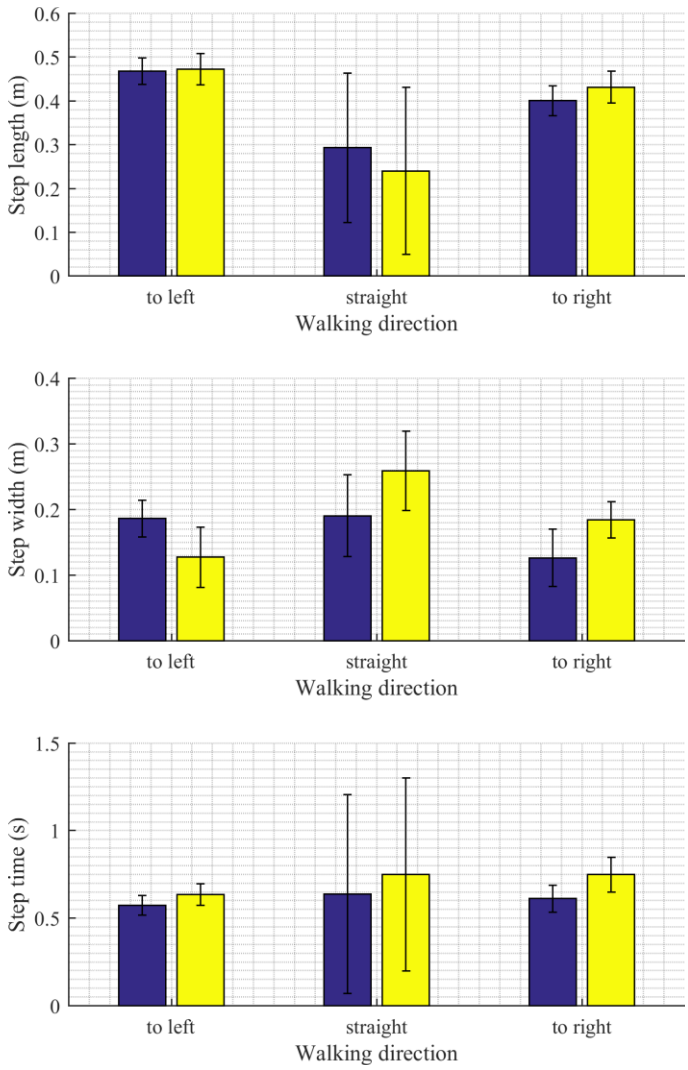


*Figure 41. Stroke subject P5, steady state*

Figure 41 shows step length, step width and step time in a case of a stroke patient P5 while continuously turning left (left panels), walking straight (middle panels) and continuously turning right (right panels). We observe that when the patient was walking straight left and right steps were shorter, with left step being somewhat longer than the right step as opposed to turning. Also, when turning left both steps were approximately equal in length, whereas when turning right left step was somewhat shorter than right step. Step width graph displays that right step was wider when the patient was turning or walking straight, but during turning in left direction left step was wider compared to right step. Step time on the other hand shows consistently lower left step time compared to right step time.

## 4.2 Starting and stopping straight line walking

Primary aim of experiments related to starting and stopping was to investigate how fast after the onset of starting and stopping signal healthy subjects and patients reach steady and to identify potential differences between healthy subjects and patients. In particular we are interested in repeating pattern in interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR. Pelvis movement in transversal plane is less reliable indication of steady gait as small changes in interaction forces/moment amplitude but not in the underlying pattern of interaction forces/moment may affect pelvis movement in a way that changes periodicity of pattern but less the amplitude of movement. Since people do not respond to these transitions identically in each repetition – they often do not start or complete walking with the same leg – responses were not averaged. Instead they will be presented individually for several repetitions of the same transition.

The starting and stopping walking experiments were performed in BAR-OG. Before starting walking, the subject was instructed to stand still until the BAR-OG operator performed countdown and then triggered a starting speed ramp as shown in Figure 42. Similarly for the stopping walking, the operator performed countdown initiating the stopping speed ramp as shown in Figure 42. Starting and stopping the speed ramp was done manually by the operator in order to give the operator at all times full control over the speed of a mobile platform instead of simply just triggering pre-programmed speed profile. In this way safety of the patients was assured.

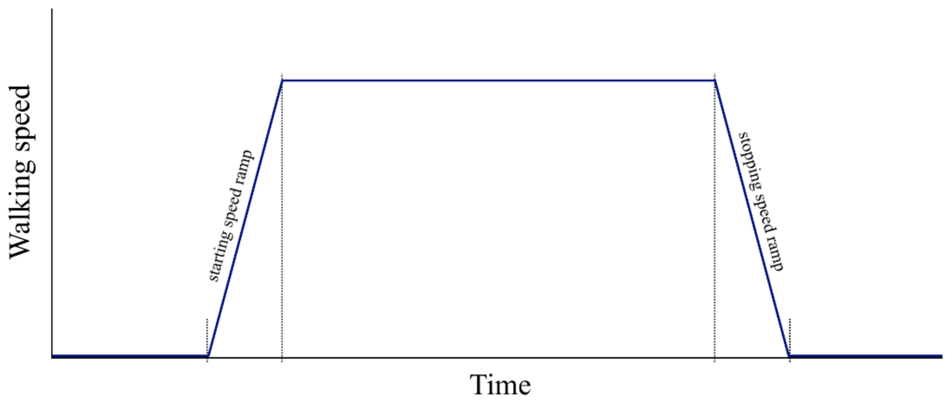


*Figure 42. Starting and stopping walking experiment.*

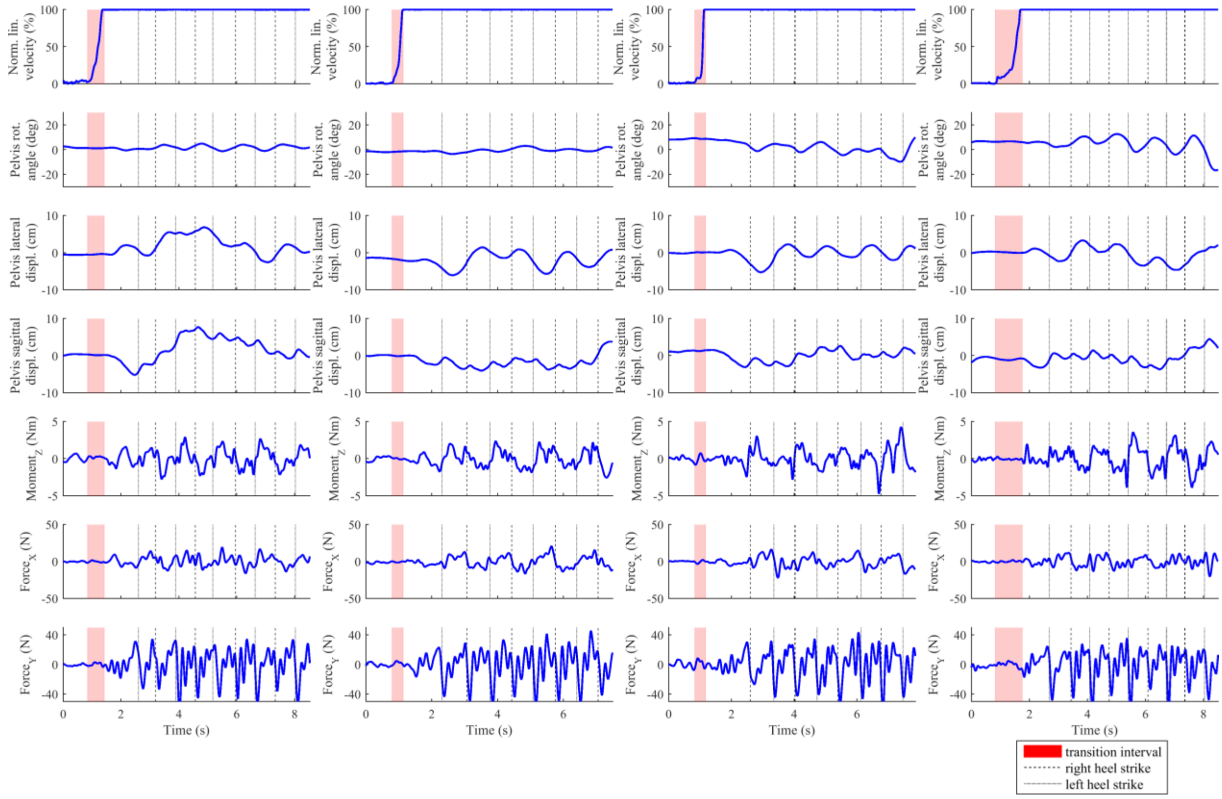


*Figure 43. Representative healthy subject, start walking*

Figure 43 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in four repetitions of starting maneuver in a representative healthy subject. Interaction forces in majority of repetitions show that healthy subject was able to develop stable gait after single step and that more steps (utmost two) to establish repetitive pattern were required only in one repetition (first repetition). We also notice that only in the first repetition pelvis movement exhibited somewhat more pronounced displacement amplitudes – e.g. displacement to the right and forward after second step – whereas in the three remaining repetitions the responses in pelvis movement were consistent.

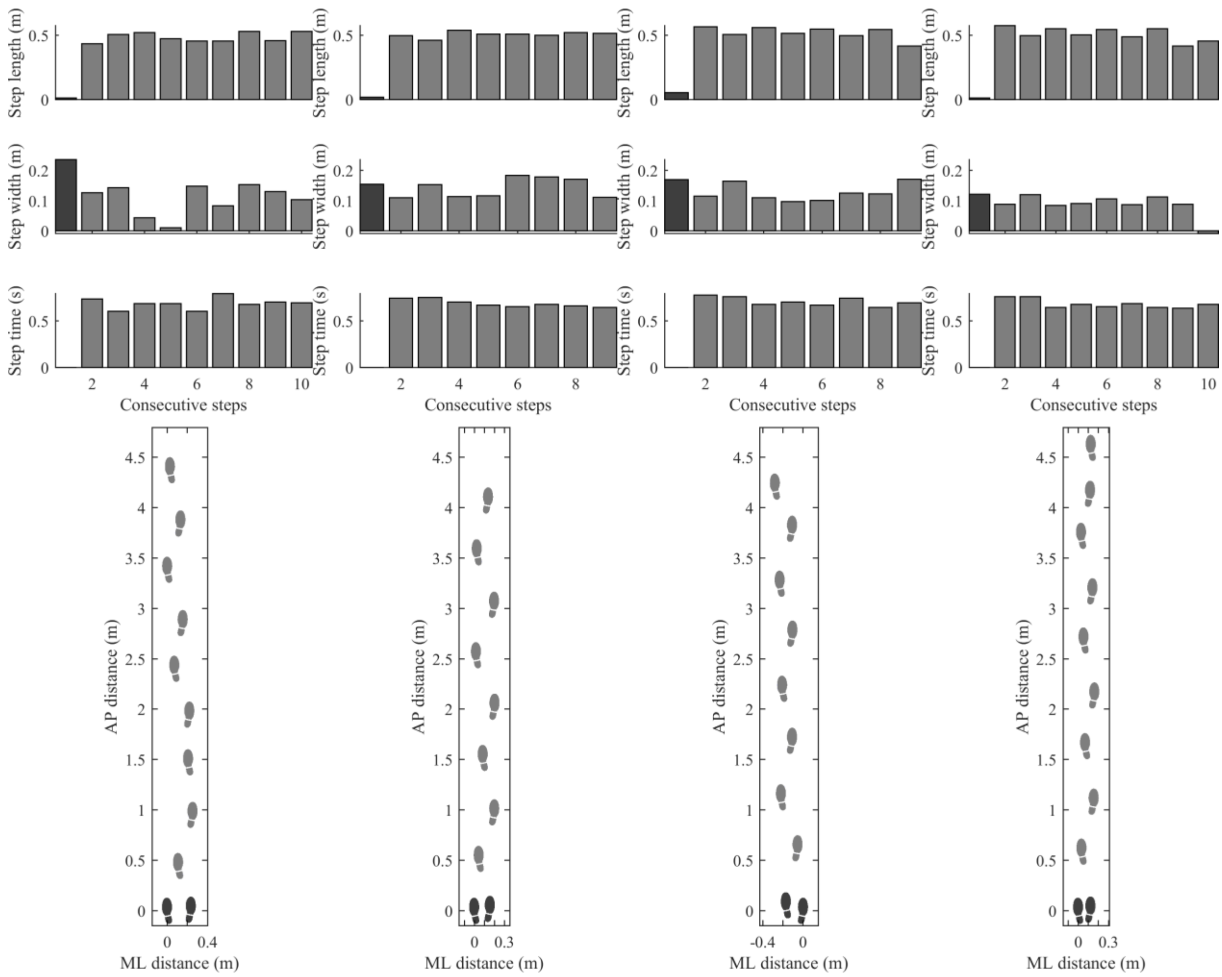


*Figure 44. Representative healthy subject, start walking*

Figure 44 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in four repetitions of starting maneuver in a representative healthy subject. We notice that in all repetitions healthy subject was able to develop consistent step length immediately after commencing walking. Step width displaced somewhat more variability in step width in first repetition that corresponds to pelvis displacement to the right. In other repetitions step width was consistent immediately after the subject started walking. On the other hand step times were consistent in all repetitions.

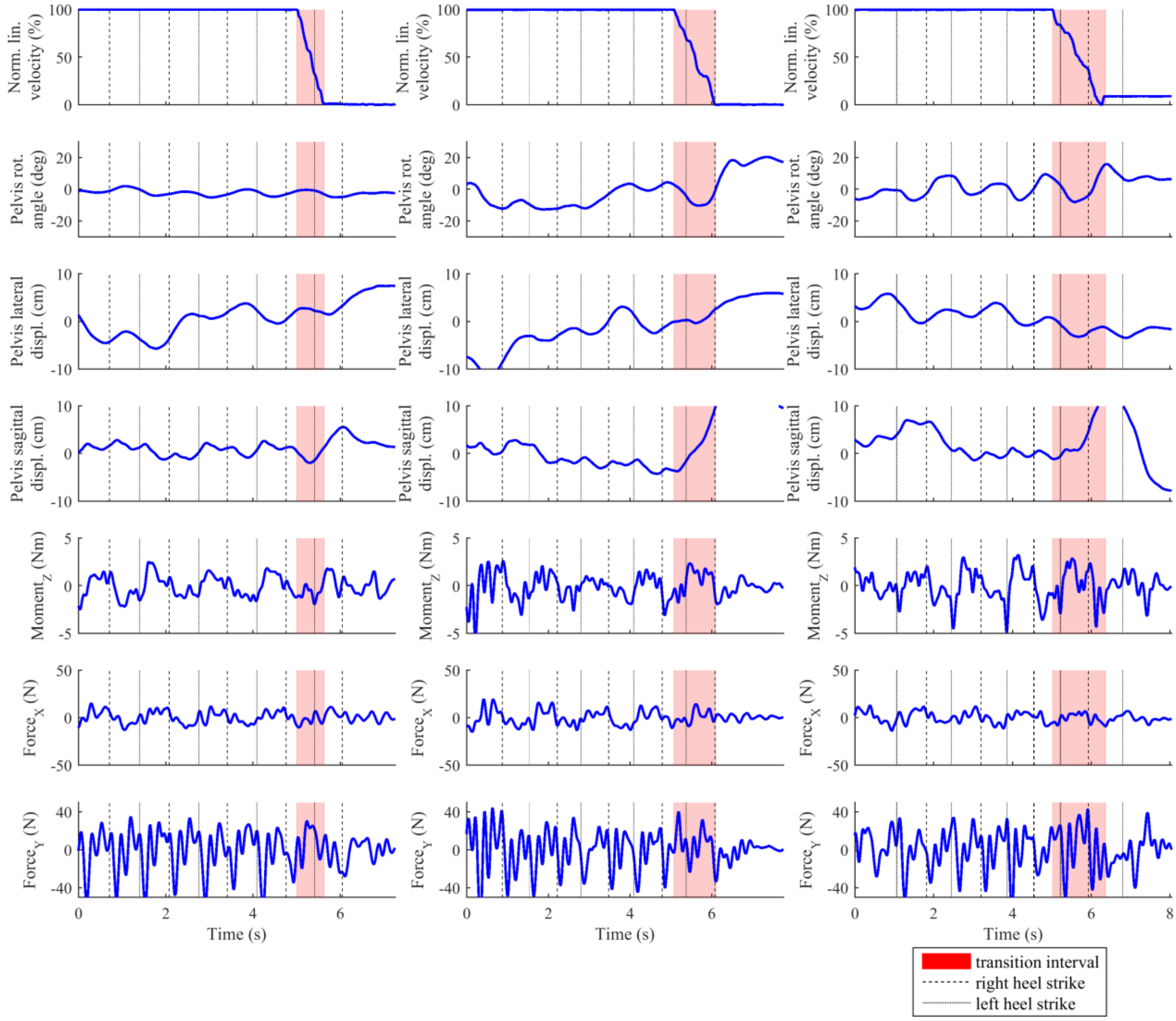


*Figure 45. Representative healthy subject, stop walking*

Figure 45 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in three repetitions of stopping maneuver in a representative healthy subject. We notice that from steady state straight walking subjects stopped movement with pelvis being approximately in neutral position in first and third trial whereas in second trial we recorded approximately 20° CCW pelvis rotation. This suggests that in second trial the subject stopped walking with feet being displaced by some distance in anterior/posterior direction. We also notice that after BAR stopped in all three cases pelvis continued to move somewhat further before it stopped due to forward momentum. In addition it took approximately two seconds after stop maneuver was initiated before periodic interaction force/moment patterns were disturbed and eventually minimized upon stopping.

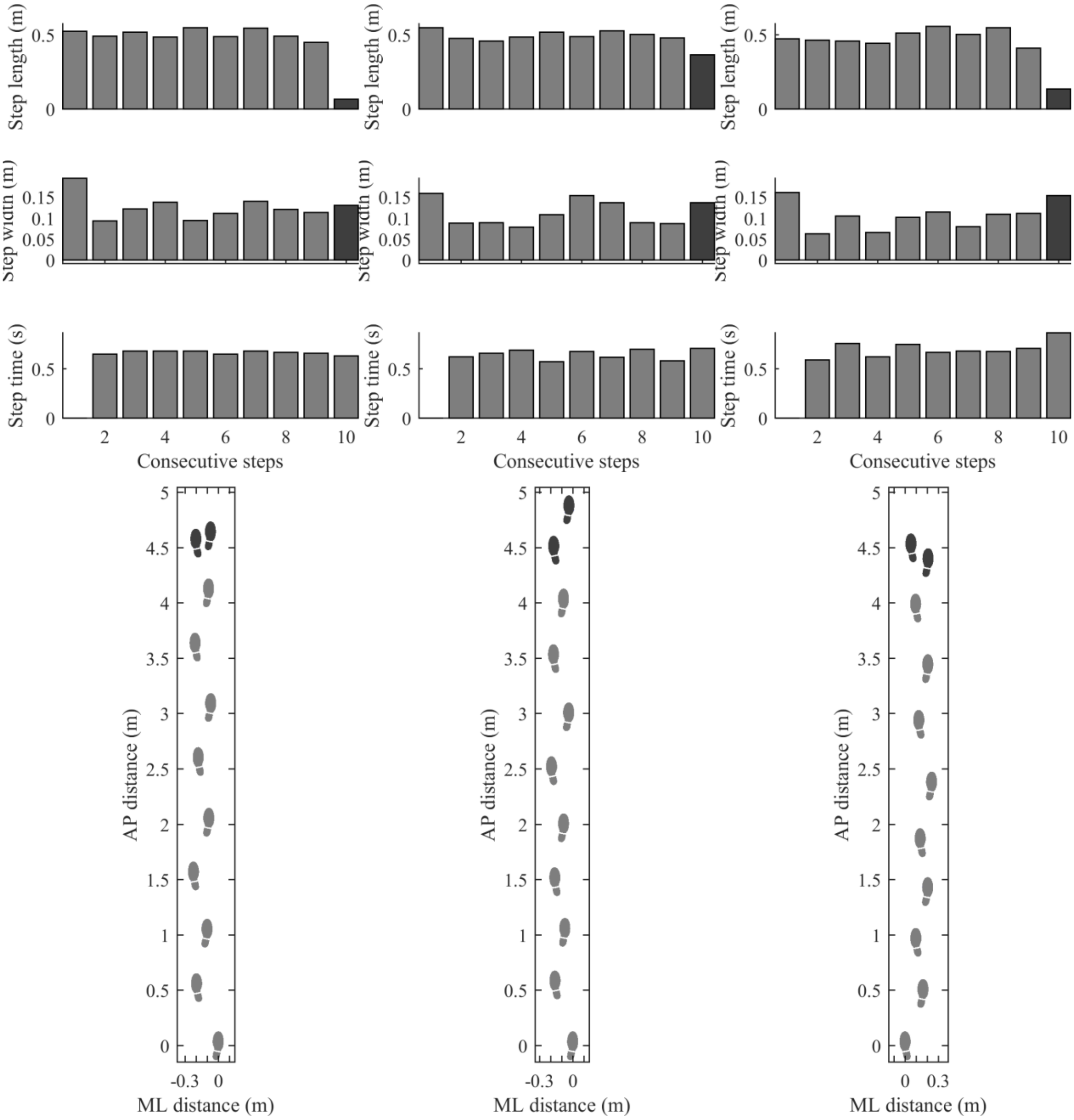


*Figure 46. Representative healthy subject, stop walking*

Figure 46 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in three repetitions of stopping maneuver in a representative healthy subject. We notice that in first and third attempt step length substantially dropped from stable recurring pattern to account for both feet being almost aligned after gait was stopped, i.e. connecting swing leg with stance leg. However in second repetition the subject stopped with both feet being displaced (hence substantial step length) so that right foot was in front of left foot (foot placement illustration). This corresponds well with substantial pelvis rotation in CCW pelvis rotation. Step width characteristics (especially in second and third repetition) show tendency to increase the step width in the last step, i.e. to increase the base of support. On the other hand step times were consistent in all repetitions.

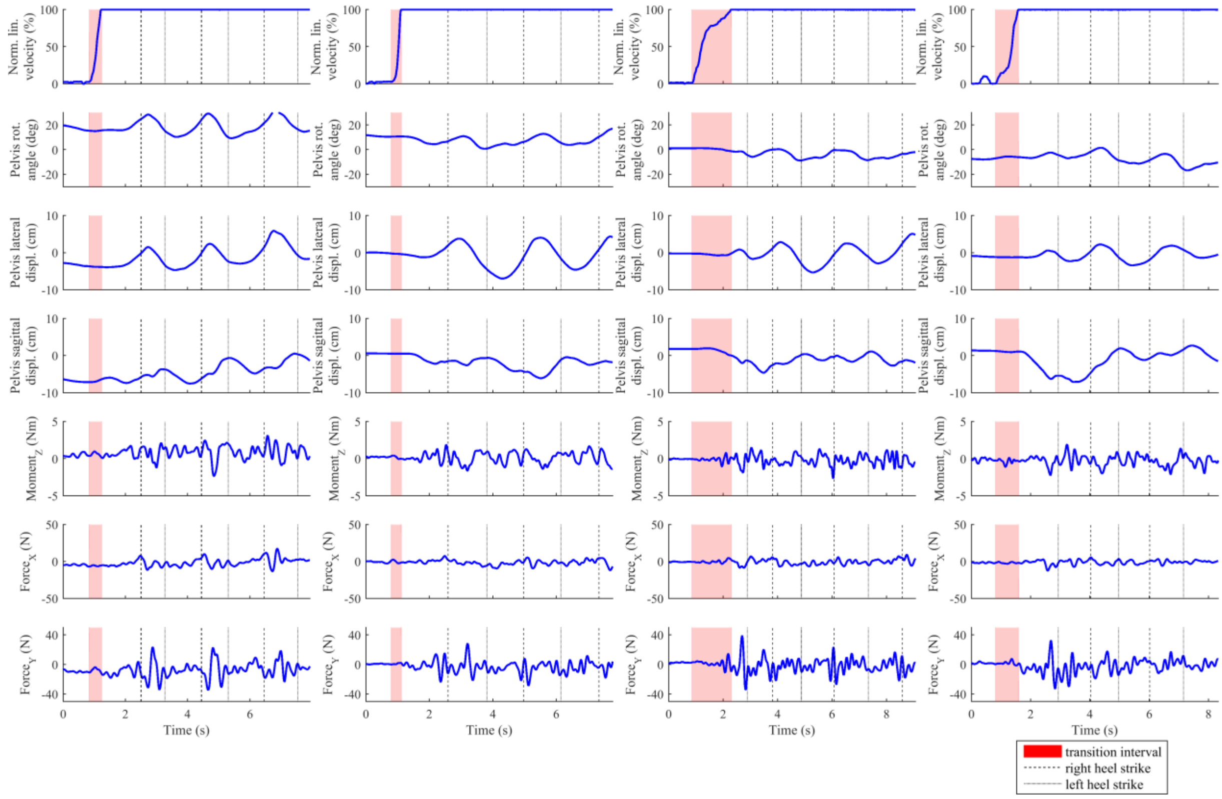


*Figure 47. Patient P1, start walking*

Figure 47 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in four repetitions of starting maneuver in patient P1. We observe somewhat more variability between repetitions when considering time needed to develop stable pattern after walking was started. In first repetition it took only one step to develop repeatable pattern in interaction forces, whereas in the remaining trials at least two steps were needed. In general, transition maneuver evoked inconsistent pattern also in pelvis movement, however higher variability even in stable state could also be attributed to the pathology.

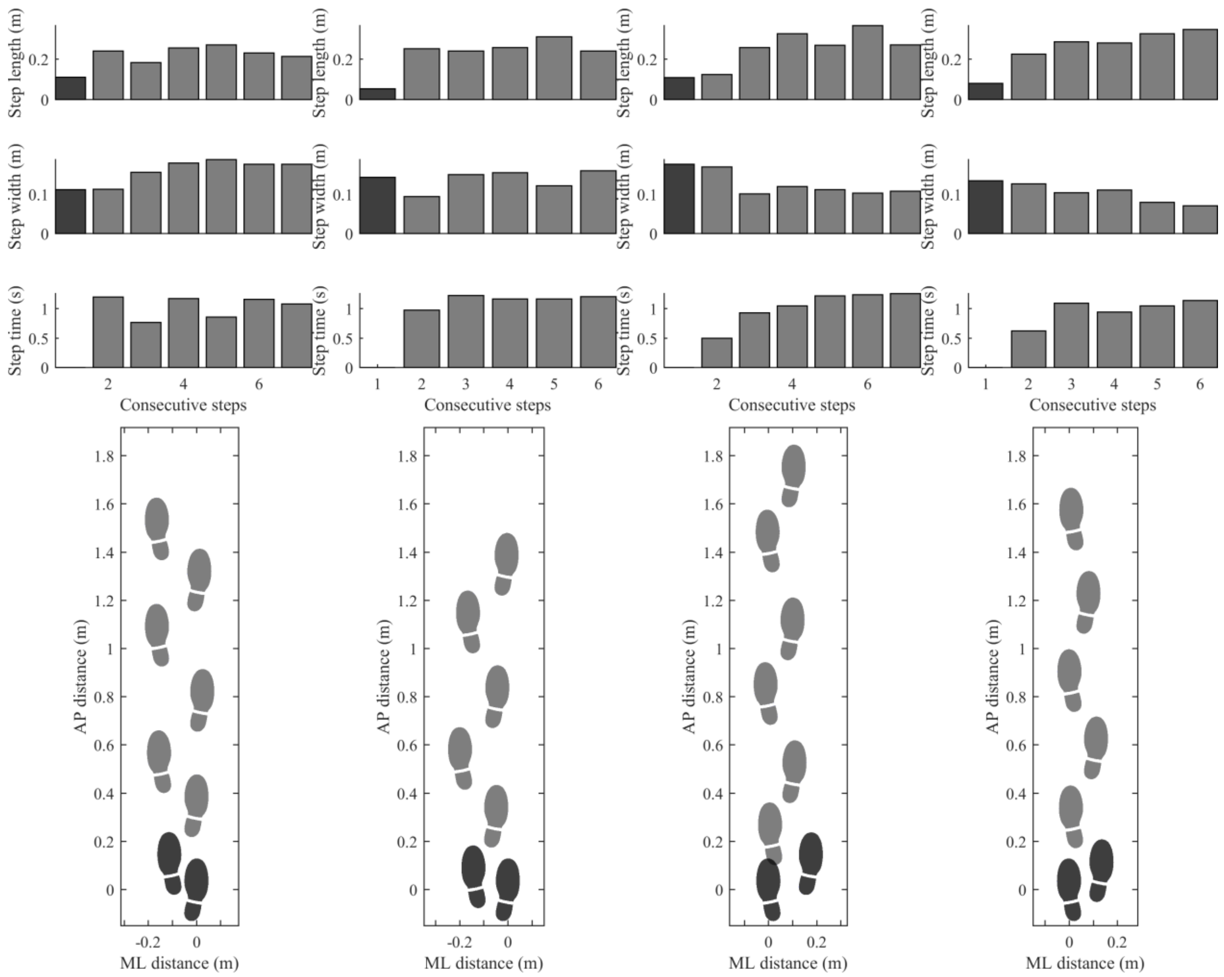


*Figure 48. Patient P1, start walking*

Figure 48 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in four repetitions of starting maneuver in patient P1. We notice that the number of steps needed before step length settles varies between repetitions and that at least two steps are needed. Inconsistent is also step width pattern; in first trial we observe increased step width, whereas in the last two trials we notice that step width decreased. We also notice that step time settles approximately in step three. From foot placement illustrations we notice that this particular subject did not prefer either left or right leg as a starting leg when initiating gait.

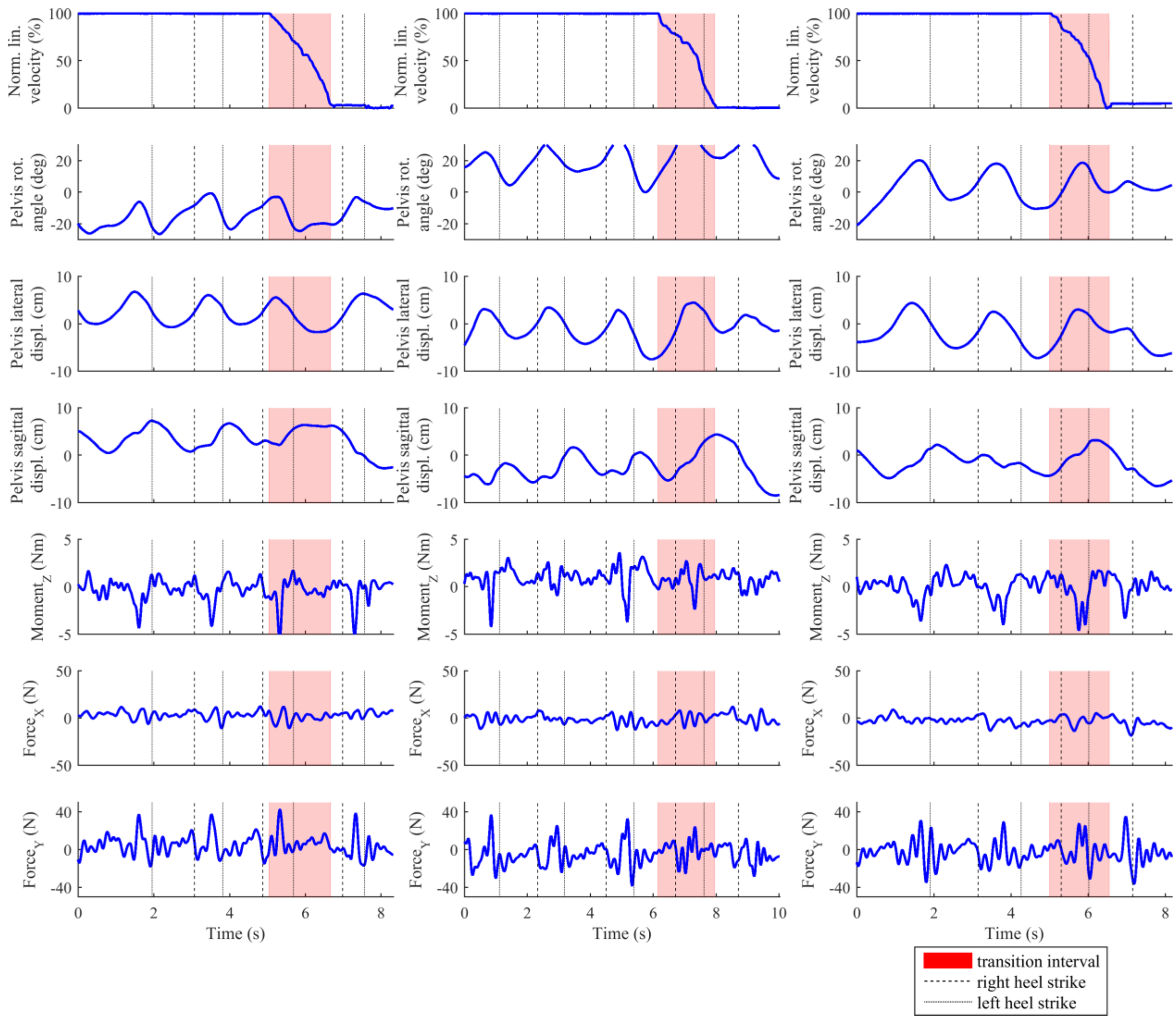


*Figure 29. Patient P1, stop walking*

Figure 49 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in three repetitions of stopping maneuver in patient P1. We notice that from steady state straight walking subjects stopped walking with pelvis being approximately in neutral position in first and third trial whereas in second trial we recorded approximately 20° CCW pelvis rotation. This suggest that in second trial the subject stopped walking with feet being displaced by some distance in anterior/posterior direction. It took approximately three seconds (approximately within two steps) after stop maneuver was initiated before periodic interaction force/moment patterns were disturbed and eventually minimized upon stropping.

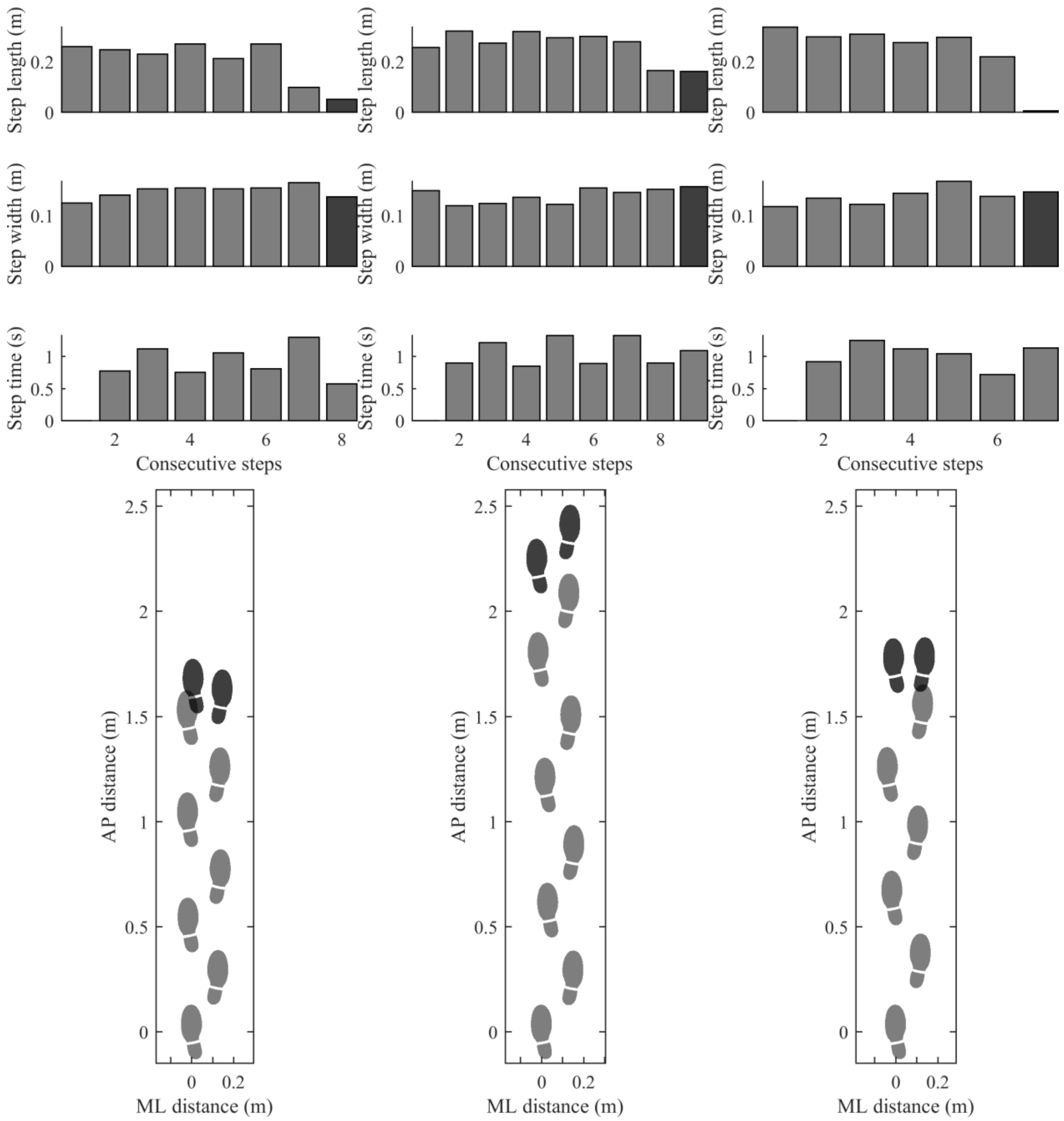


*Figure 50. Patient P1, stop walking*

Figure 50 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in three repetitions of stopping maneuver in patient P1. We notice that in first and third attempt step length substantially dropped from stable recurring pattern to account for both feet being almost aligned after gait was stopped, i.e. connecting swing leg with stance leg. However in second repetition the subject stopped with both feet being displaced (hence substantial step length) so that right foot was in front of left foot (foot placement illustration). This corresponds well with substantial pelvis rotation in CCW pelvis rotation. Step width characteristics show consistent step width in all repetitions, i.e. base of support was approximately the same during walking and upon stopping.

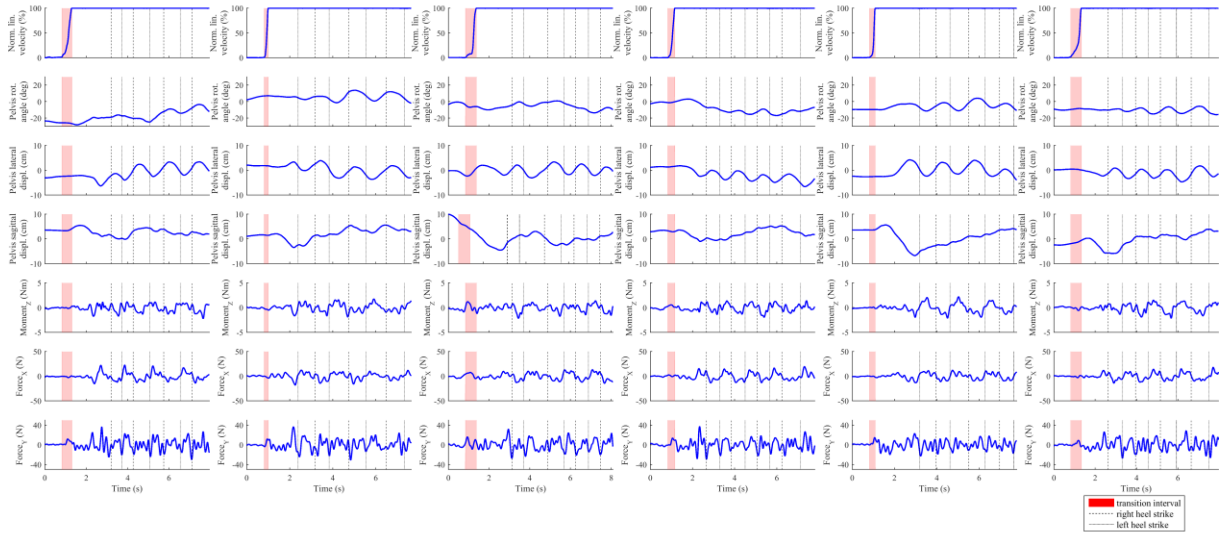

*Figure 51. Patient P2, start walking*

Figure 51 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in six repetitions of starting maneuver in patient P2. We notice that in all repetitions approximately two seconds were needed after the onset of initiating signal before the first foot strike. We also notice that the subject preferred to start walking with left leg (trials 1, 3, 4, 6) as opposed to right leg (trials 2, 5). This is accompanied with appropriate pelvis displacement in medio/lateral direction – left pelvis displacement when walking was initiated with right leg and right pelvis displacement when initiating gait with left leg. Except from first repetition pelvis rotation was in all other trials approximately aligned with neutral position. Finally, interaction force pattern shows that considerable gait repeatability was obtained after first step.

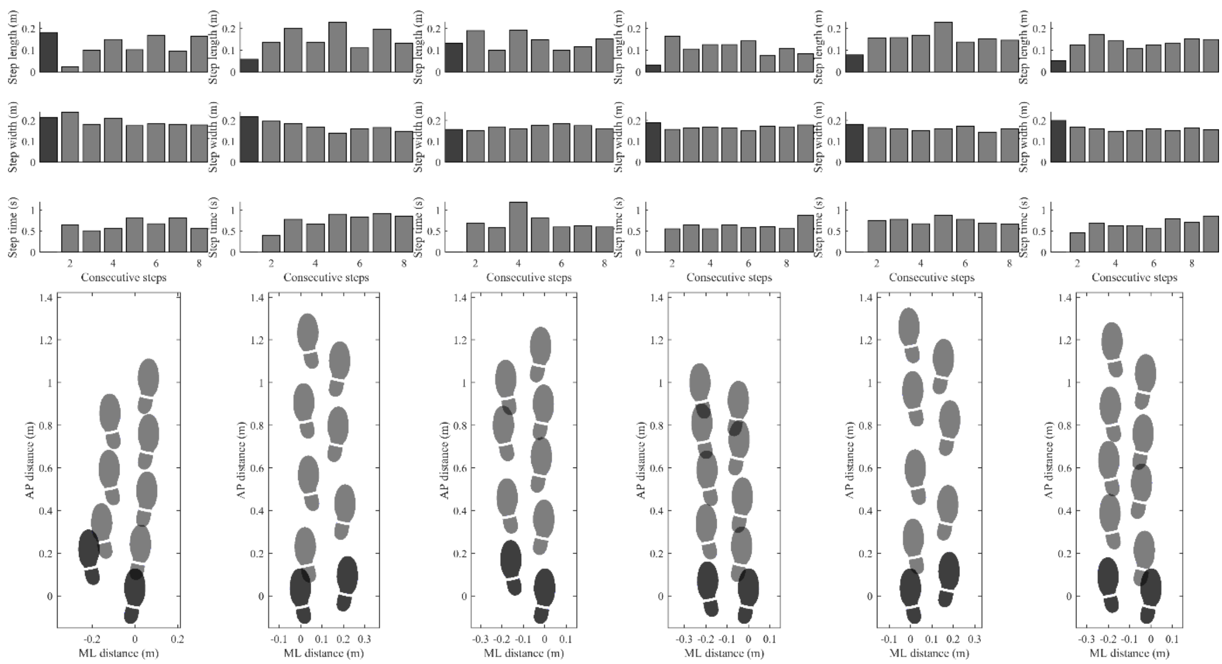

*Figure 52. Patient P2, start walking*

Figure 52 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in six repetitions of starting maneuver in patient P2. In first trial we notice substantial distance between both feet in anterior/posterior direction which corresponds with pelvis rotation in CCW direction. Particularly in first four trials the variability in step length was higher with right step being longer than the left step. In the remaining two steps step length was consistent after initial step. Step width shows consistent pattern immediately after first step in all repetitions. The same is true for step times where consistent step time was obtained in step two after initiating gait at the very latest. As already observed above footprint illustrations show that the subject initiated walking with left leg in trials 1, 3, 4, 6 and with right leg in trials 2, 5.

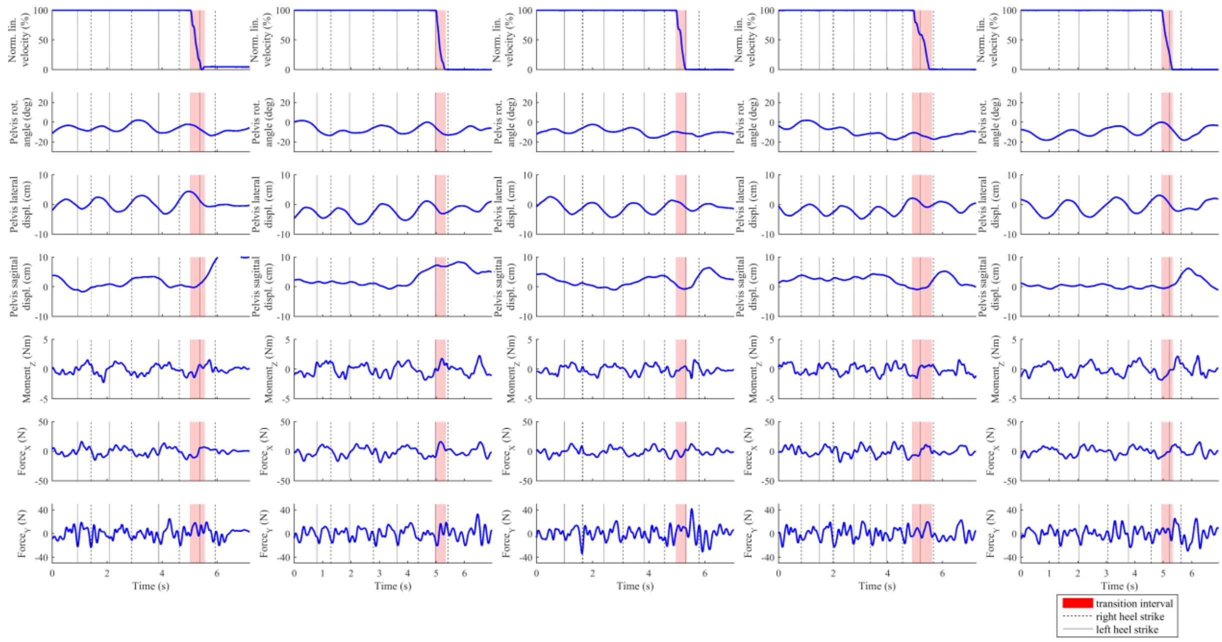


*Figure 53. Patient P2, stop walking*

Figure 53 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in five repetitions of stopping maneuver in patient P2. We notice that in all trials pelvis was approximately aligned with neutral position after the subjects stopped walking which suggests that after stopping both feet were aligned. It took approximately two seconds after stop maneuver was initiated before movement stopped.

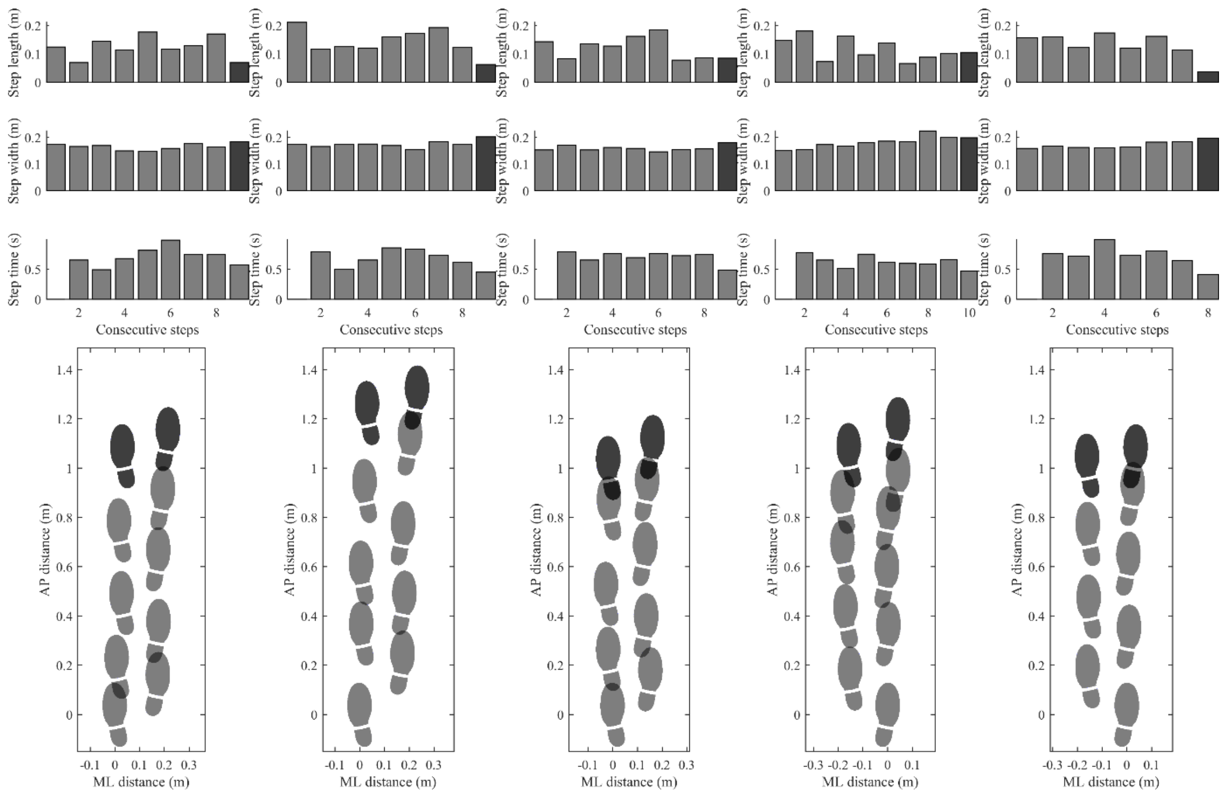


*Figure 54. Patient P2, stop walking*

Figure 54 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in five repetitions of stopping maneuver in patient P2. We observe that in all trials after the subject stopped walking there was some distance present between both feet in anterior/posterior direction that indicates more anterior position of right foot compared to left foot. We also notice that prior to initiating stopping maneuver step length displayed inconsistent pattern with high variability. On the other hand step width was very consistent before stopping and remained approximately the same also after stopping. Step time patterns again show more inconsistent patterns before initiating stopping. Footprint illustrations confirm more anterior right leg position after settling in standing.

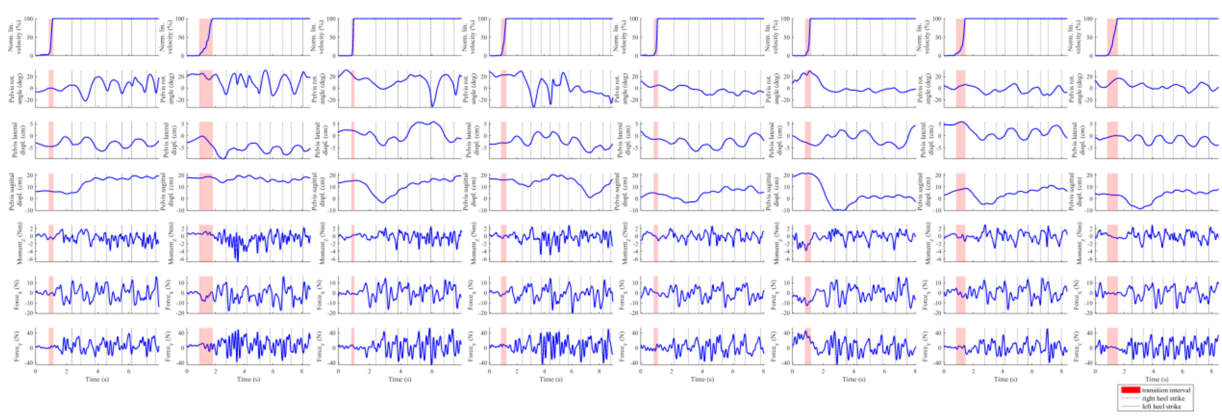

*Figure 55. Patient P3, start walking*

Figure 55 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in eight repetitions of starting maneuver in patient P3. We notice that between presented trials gait initiation pattern exhibit high variability. While some display high repeatability (e.g. trials 1 and 8) other trials show inconsistent pattern even after several steps.

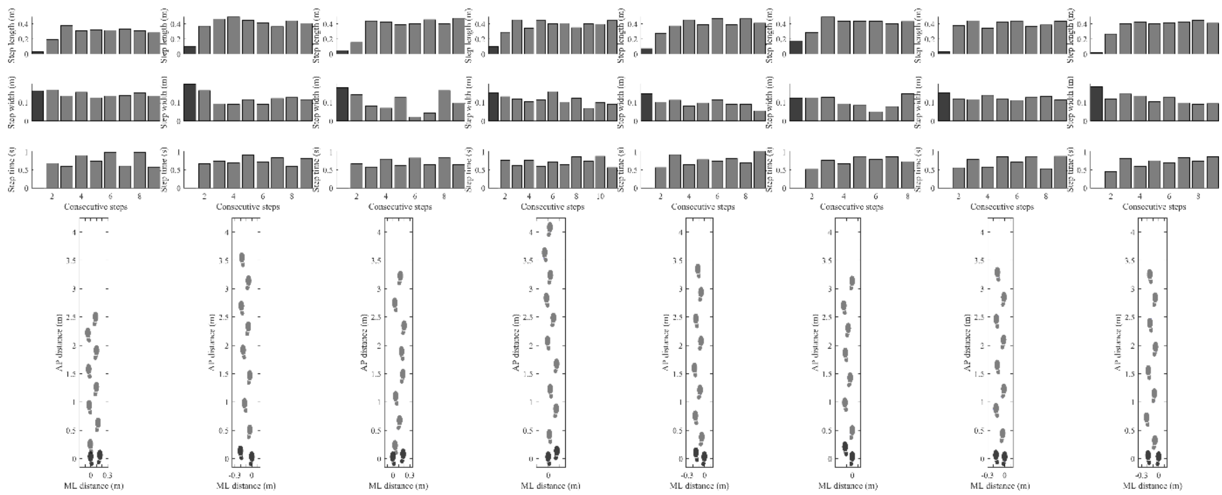

*Figure 56. Patient P3, start walking*

Figure 56 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in eight repetitions of starting maneuver in patient P2. We notice that in all trials at least two steps were needed for step length to settle whereas after two steps step length remains approximately unchanged. First attempt is characterized with somewhat shorter step length compared to other trials which resulted in shorter distance being covered (as visually displayed in footprint illustrations). Step width patterns show more variability within trial – i.e. considerable differences in step width in consecutive steps of individual trials (e.g. trial 3) – and inconsistent pattern between trials. The same is true for step time characteristics where no consistent pattern could be identified across trials. Also, footstep illustrations show that to great extent the patient did not prefer neither left nor right leg as a starting leg when initiating walking.

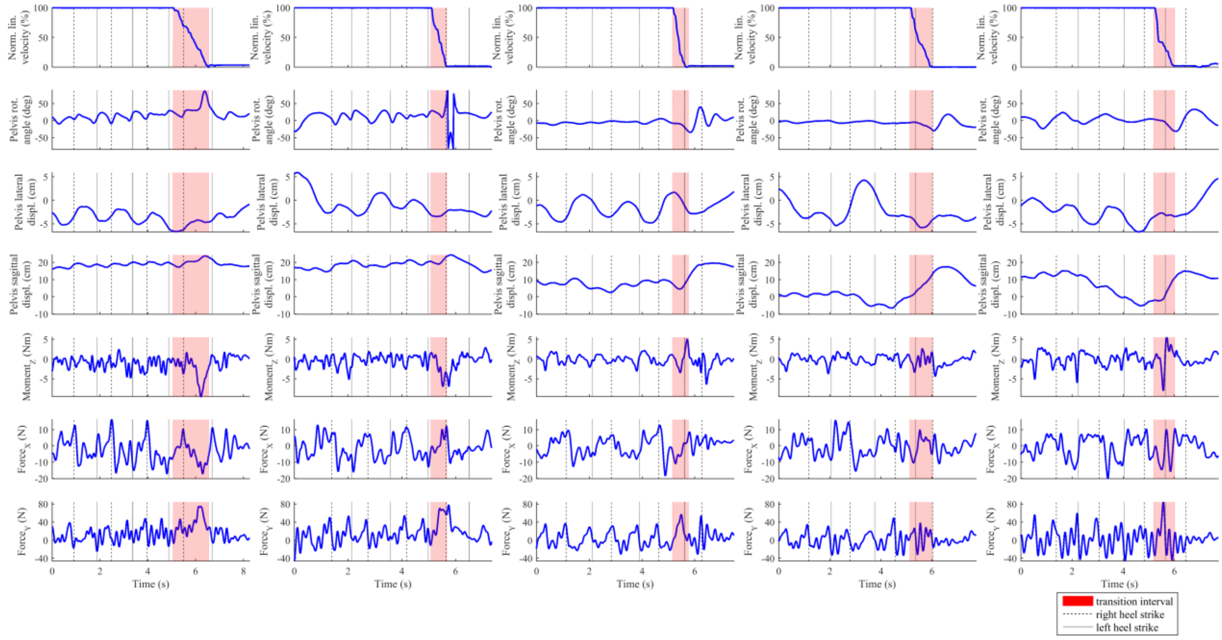


*Figure 57. Patient P3, stop walking*

Figure 57 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in five repetitions of stopping maneuver in patient P3. We notice that the majority of movement associated to gait stopping is completed within two steps – repeatable pattern of interaction forces is disturbed and considerably diminishes the amplitude. On the other hand we notice that initiating stopping maneuver is accompanied with somewhat larger pelvis rotation.

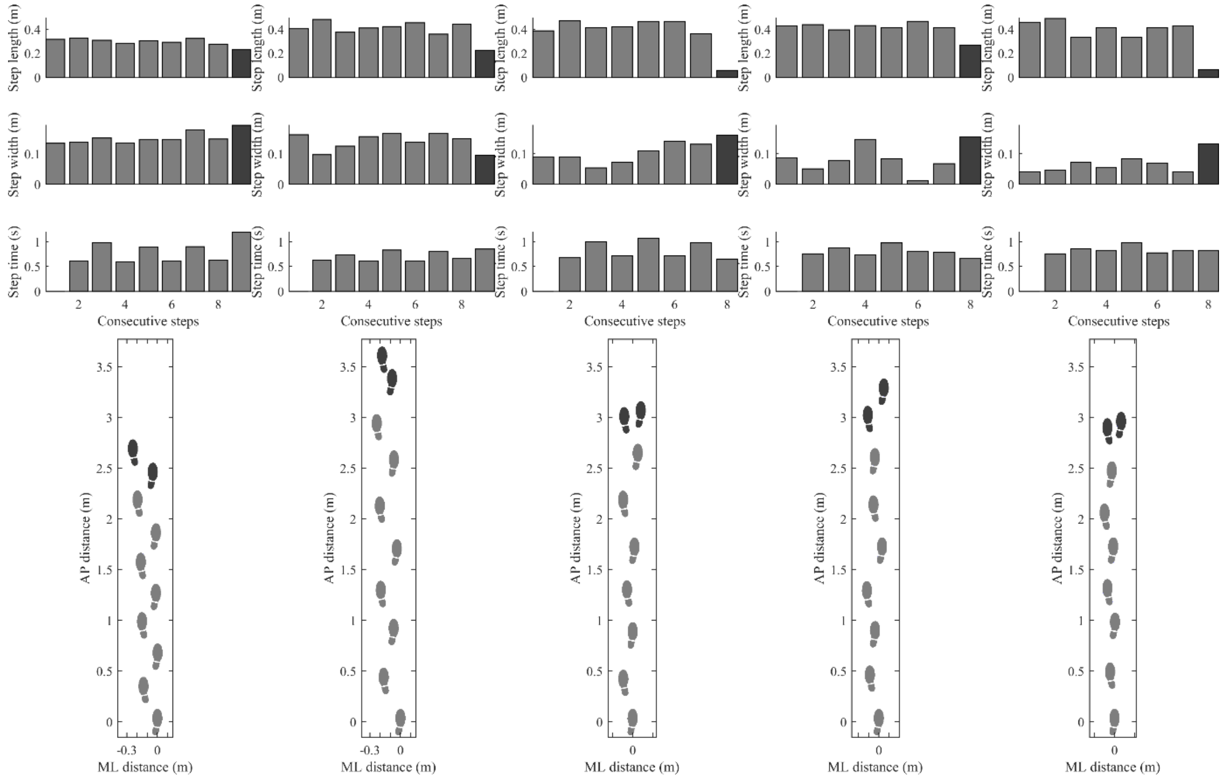


*Figure 58. Patient P3, stop walking*

Figure 58 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in five repetitions of stopping maneuver in patient P3. We observe that in three trials after the subject stopped walking there was a short distance present between both feet in anterior/posterior direction that indicates more anterior position of one leg with respect to other whereas in two remaining trials both feet were aligned resulting in almost zero step length. In general step length pattern was very consistent across trial. On the other hand before initiating stopping maneuver step width displays considerable variability. Step time patterns again show more consistent patterns before initiating stopping. Footprint illustrations show that in three trials after the subject stopped walking there was a short distance present between both feet in anterior/posterior direction that indicates more anterior position of one leg with respect to the other whereas in two remaining trials both feet were approximately aligned.

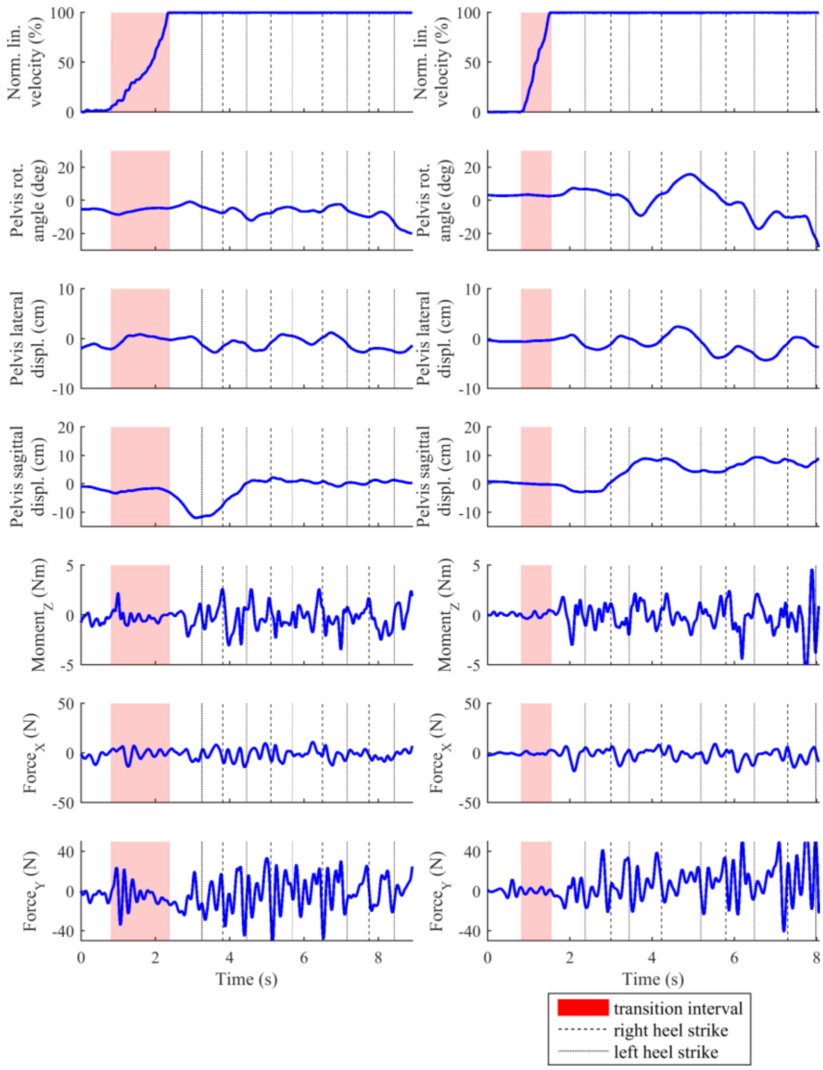


*Figure 59. Patient P4, start walking*

Figure 59 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in two repetitions of starting maneuver in patient P4. In two presented trials pelvis displacement in medio/lateral direction shows considerable resemblance in terms of left/right movement. We also notice that within two steps similar characteristics appear in interaction forces.

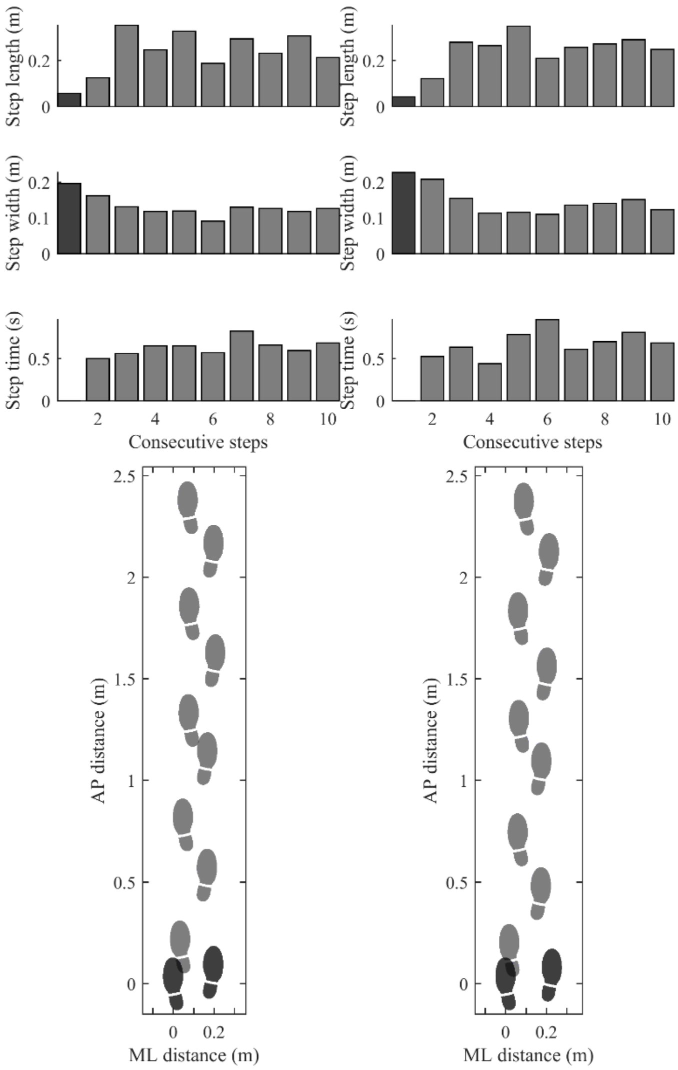


*Figure 60. Patient P4, start walking*

Figure 60 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in two repetitions of starting maneuver in patient P4. We notice that final step length was obtained within two steps – however step length variability in subsequent steps was evident. Both trials exhibit gradual step width reduction in two steps after initiating gait. Step time again displays more variability in steps following the onset of gait initiation. Also, footprint illustrations show that in both trials the patient preferred to initiate walking with left leg.

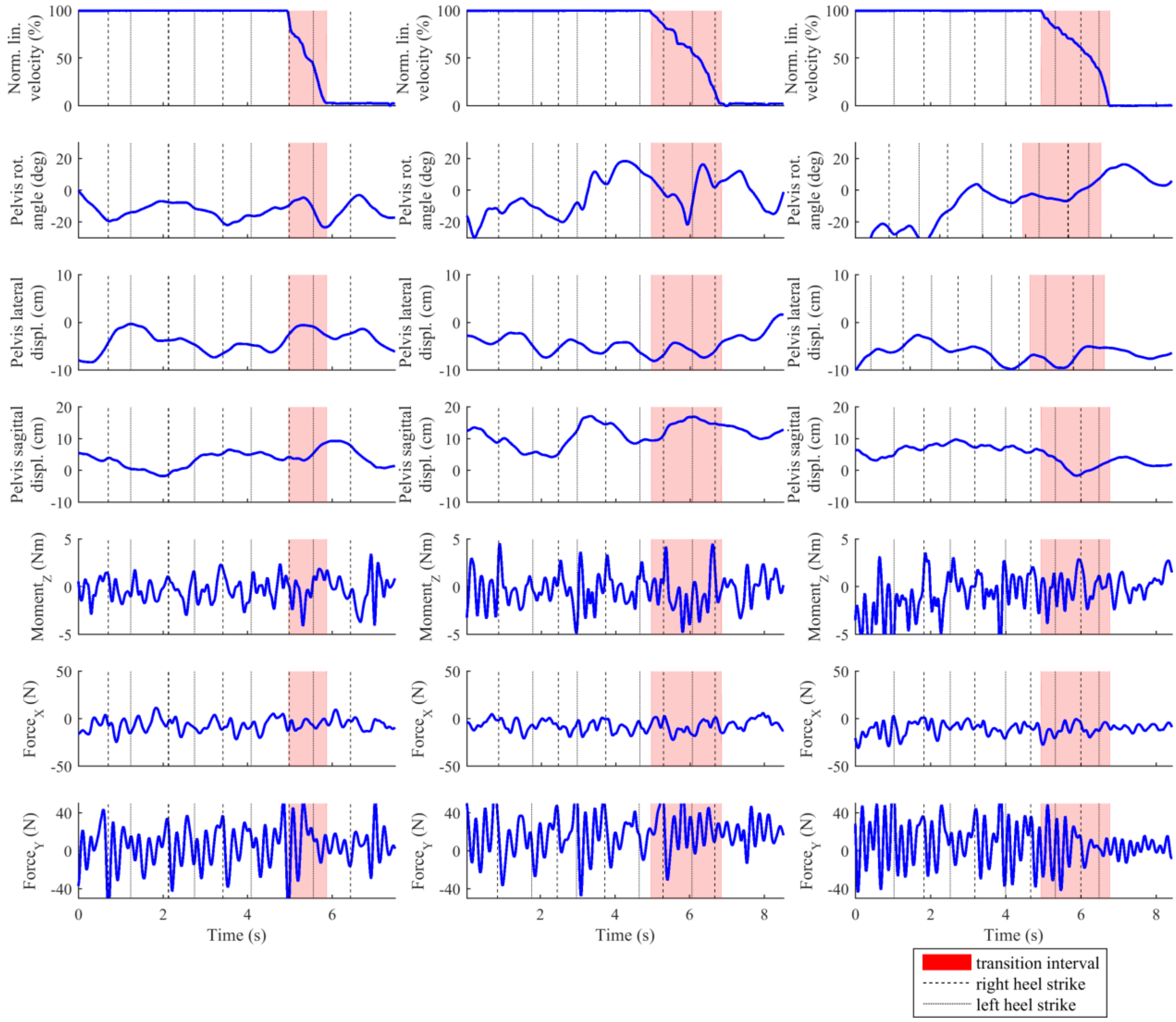


*Figure 61. Patient P4, stop walking*

Figure 61 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in three repetitions of stopping maneuver in patient P4. We notice that the majority of movement associated to gait stopping is completed approximately within two seconds. In general pelvis movement as well as interaction forces exhibit inconsistent pattern with high variability.

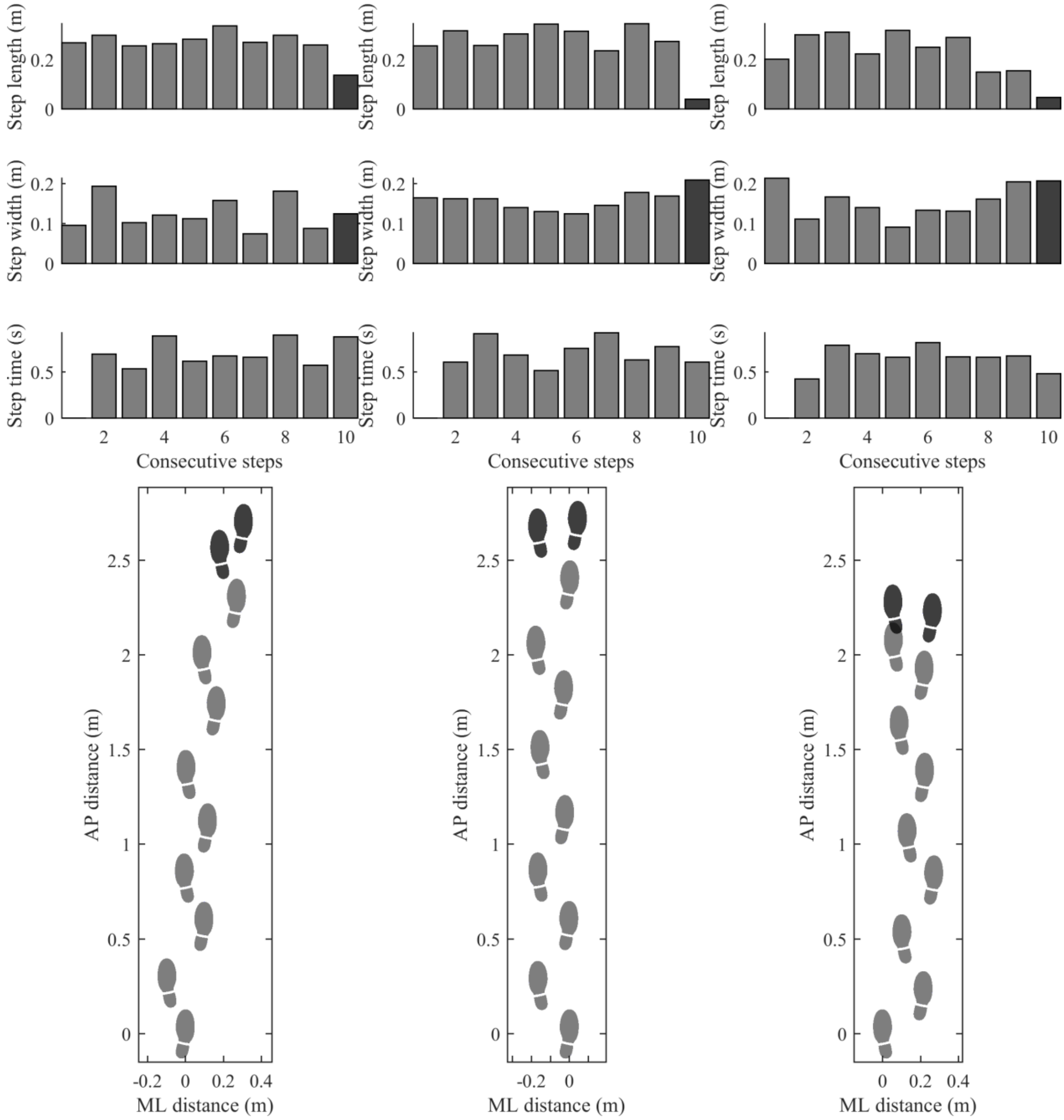


*Figure 62. Patient P4, stop walking*

Figure 62 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in three repetitions of stopping maneuver in patient P4. Also in step length pattern we can observe high variability prior to stopping maneuver was initiated. The same is true for step width and step time where unstable step width and step time is noted in steps before gait was stopped.

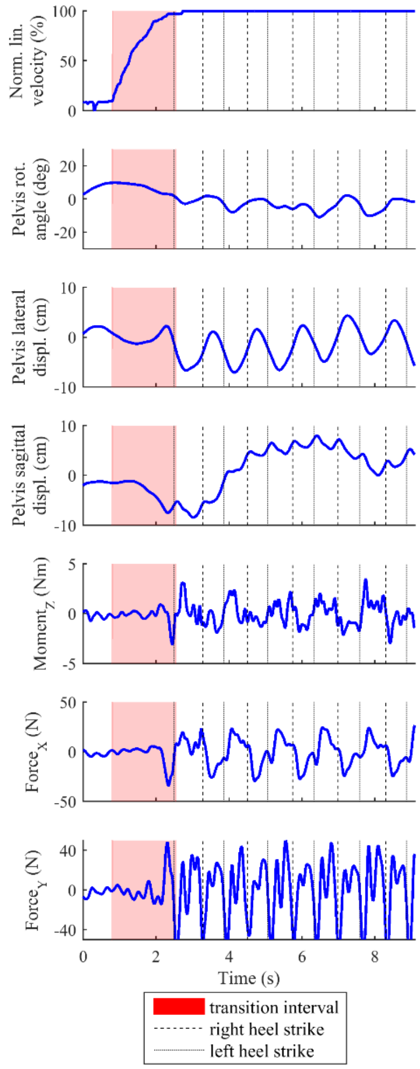


*Figure 63. Patient P5, start walking*

Figure 63 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to start signal in one case of starting maneuver in patient P5. Pelvis movement in transversal plane as well as interaction forces show that this patient was able to develop stable gait after single step. Furthermore repeatability of pelvis movement and interaction forces/moment is high. We also notice that interaction force in anterior/posterior direction displays different pattern during right and left steps.

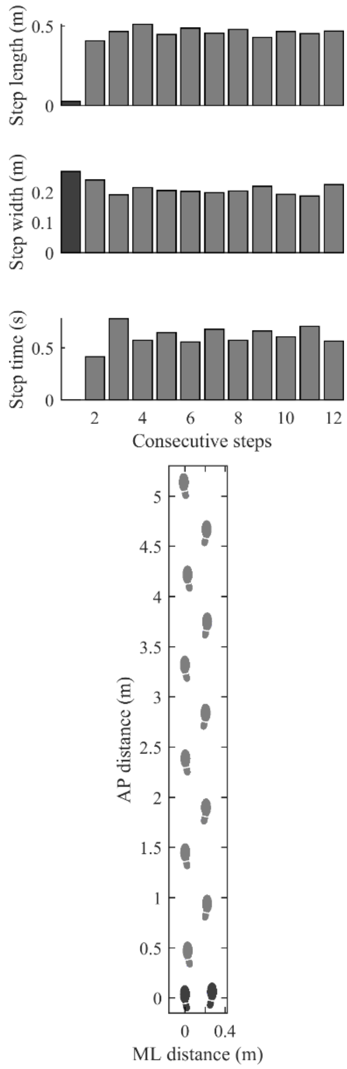


*Figure 64. Patient P5, start walking*

Figure 64 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of starting maneuver in one case of starting maneuver in patient P5. We notice that patient was able to develop consistent step length, step width and step time immediately after commencing walking.

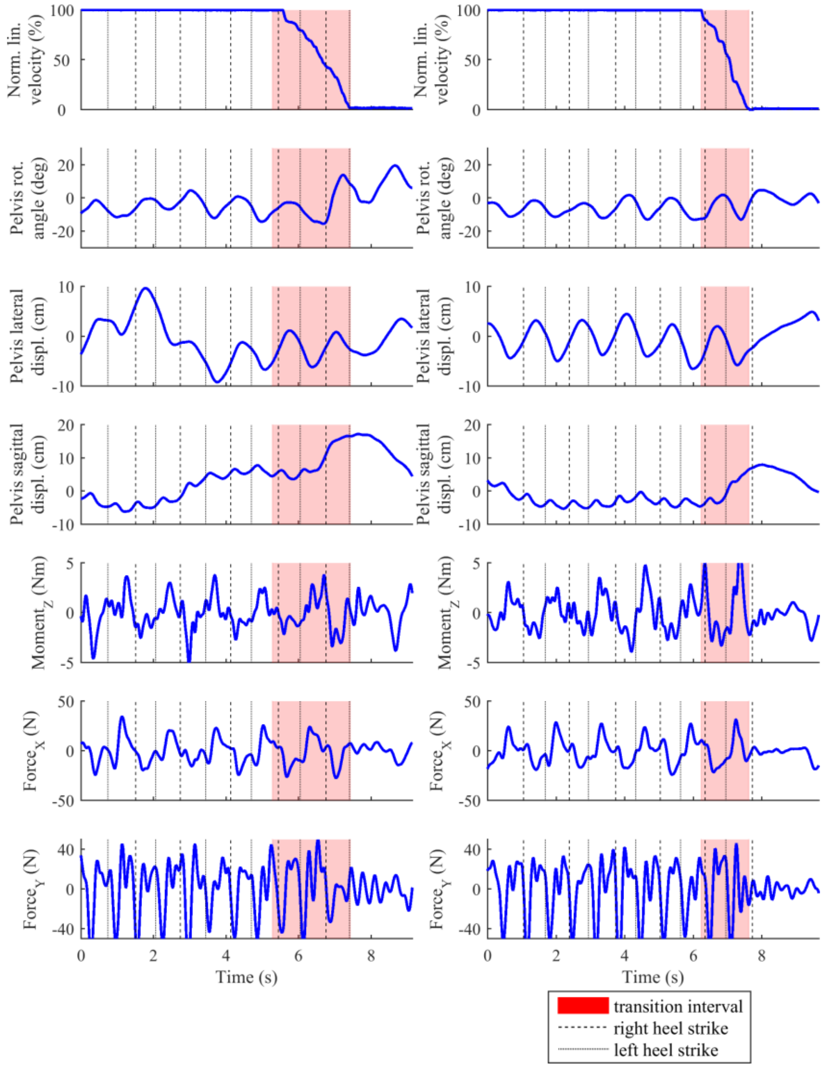


*Figure 65. Patient P5, stop walking*

Figure 65 shows pelvis movement in transversal plane (sagittal and lateral displacement of pelvis and pelvis rotation) and interaction forces in medio/lateral and anterior/posterior direction and moment around vertical axis between the subject's pelvis and pelvis element of BAR with respect to stop signal in two repetitions of stopping maneuver in patient P5. We notice that in both cases pelvis movement and interaction forces/moments display almost the same pattern before as well as after initiating stopping maneuver. We also observe that the transition was completed in a single step – very repeatable pattern of interaction forces was terminated in one step.

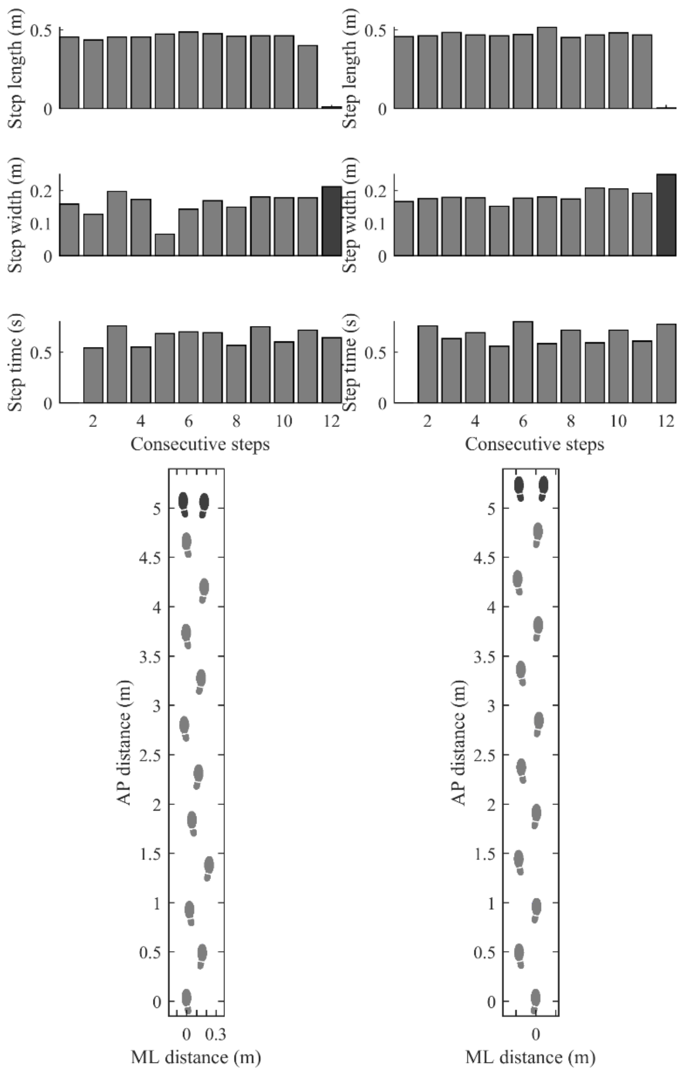


*Figure 66. Patient P5, stop walking*

Figure 66 shows step length, step width and step time as well as illustration of foot placement in consecutive steps following the onset of stopping maneuver in two repetitions of stopping maneuver in patient P5. We notice very consistent step length pattern that terminated in a single step. Step width shows less consistency, particularly in first trial. In both trials step width in final step is largest. Step time graphs again show minor differences between left and right step times.

# 5. Conclusions

Experimental evaluation of gait characteristics after being subjected to selected walking maneuvers that may impose fall-threatening conditions for neurologically impaired subjects shows that no uniform responses should be expected among patients.

In general it is true that when walking straight or turning neurologically impaired subjects tend to lengthen the support phase on their better leg which also results in shifting the center of mass accordingly in the same direction. Nevertheless results have shown that compared to straight walking center of mass during turning only slightly shifts further in the direction of turning to account for change in direction of walking, which is very different from the behavior of healthy subjects. This observation is consistent over the stroke subjects P1-P4; they all tended to shift their weight toward unimpaired side. The subject P5 who was the only one who could walk at a speed close to the one generally considered being sufficient for independent walking in the community.

For neurologically impaired subjects there is no rule as to whether step length during straight walking or turning should be longer on impaired or unimpaired side. Patients seem to walk with step length asymmetry that does not necessarily prefer shorter or longer steps on impaired side. Instead step length characteristics are in this sense mixed. We have however noticed that compared to straight walking step length symmetry to some extent improved if patient was walking in the direction of longer steps, e.g. if in straight walking left step was longer turning to the left reduced step length asymmetry considerably. On the other hand step width pattern was very consistent; when walking straight step width was approximately the same for left and right side, whereas when turning in left (right) direction left (right) step was wider. Step times displayed lengthening the support on unimpaired side.

Finally initiating and stopping the gait showed that patients have developed mechanisms that enable them to settle at repeatable pattern within several steps. While the number of steps before repeatable pattern was established varies between patients we noticed that utmost three steps were sufficient. In that sense there was little difference between the tested stroke subjects and the group of healthy subjects. All subjects were quite capable of starting and stopping the movement. The difference between the patients and healthy was primarily in the variability of performing these maneuvers and in the number of steps needed to start or stop walking. While some of the variability comes from the variable nature of initiating increasing and decreasing of the speed which was in hands of the mobile platform operator due to safety we can conclude that in neurologically impaired population we may expect on one hand more variable behavior but on the other hand also quite consistent functioning.

If we look upon the results presented in this deliverable from the point of view that relates to control of EMY exoskeleton which will be used to augment balancing behavior of selected stroke subjects we may draw a conclusion that as far as maneuvers such as turning, starting/stopping and increasing/decreasing the speed of walking are concerned the EMY exoskeleton should be providing as transparent behavior as possible. Our group of selected stroke subjects tested was very diverse in terms of their walking abilities and walking speeds, however, they were all very capable to perform the proactive balancing tasks provided that the speed of movement was the one they selected.