ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA CAMPUS DI CESENA
DIPARTIMENTO DI INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI"

Corso di Laurea Triennale in
Ingegneria Biomedica

EXPERIMENTAL CHARACTERIZATION OF ANTICIPATORY POSTURAL ADJUSTMENTS PRIOR TO STEP INITIATION

Tesi di Laurea Triennale in
LABORATORIO DI INGEGNERIA BIOMEDICA

RELATORE:
Prof. Lorenzo Chiari

PRESENTATA DA:
ALESSANDRO GOZZI

CORRELATORE:
Ing. Mattia Corzani

SESSIONE ESTIVA
ANNO ACCADEMICO 2018-2019

Alla mia famiglia

SUMMARY

ABSTRACT

Italian

L'inizio del cammino/passo è una task funzionale usata per investigare come il sistema nervoso centrale controlla l'equilibrio. È un esercizio che richiede l'integrazione di molteplici informazioni sensoriali e richiede il controllo e la coordinazione di numerosi muscoli scheletrici distribuiti su tutto il corpo. Il corpo mette in atto azioni per il controllo dell'equilibrio durante, dopo e anche prima dell'esecuzione di questo esercizio. Comprendere come il sistema nervoso centrale agisce durante l'inizio del cammino/passo è un prerequisito per identificare disordini motori in popolazioni che presentano problemi del sistema posturale.

Questo esperimento ha preso in esame i movimenti anticipatori al cammino e si propone di caratterizzarli e osservarne il loro cambiamento in risposta a differenti variabili esterne.

Sono stati presi in esame 5 soggetti sani. La strumentazione utilizzata consiste in una pedana di forza e tre IMU (2 per le caviglie e 1 per il tronco). I soggetti hanno eseguito 15 task per 3 volte ciascuna a seguito di apposite istruzioni date dall'esaminatore. Dai segnali ottenuti sono stati estratti il valore del picco del centro di pressione (CoP) antero-posteriore (AP) e medio-laterale (ML), il tempo che intercorre tra inizio APA e picco e infine il valore del picco AP e ML dell'accelerazione del tronco.

Dai risultati è emerso che la velocità di esecuzione e il numero di passi modificano durata dell'APA e valore dei picchi del CoP. Variare la lunghezza del passo ha influito quasi esclusivamente sui valori dei picchi del CoP. È interessante notare come variare il tempo di reazione, inserire task cognitivi ed eseguire il compito ad occhi chiusi abbia portato a una diminuzione di durata e time-to-peak e un aumento dei picchi ML e AP.

English

The gait/step initiation is a functional task used to investigate how the central nervous system controls balance. It is an exercise that requires the integration of multiple sensory information and requires the control and coordination of numerous skeletal muscles distributed throughout the body. The body responds controlling the balance

during, after and even before the execution of this exercise. Understanding how the central nervous system acts during the gait/step initiation is a precondition to identify motor disorders in populations that present problems with the postural system.

This experiment has examined anticipatory movements on the path, and aims to characterize them and observe their changes in response to different external variables.

Five healthy subjects were examined. The instrumentation consists of a force platform and three IMUs (2 for the ankles and 1 for the trunk). The subjects performed 15 tasks 3 times each following specific instructions given by the examiner. The algorithm extracted the peak value of the antero-posterior (AP) and middle-lateral (ML) centre of pressure (CoP), the time between APA onset and APA peak, the AP and ML peak value of trunk acceleration.

The results showed that the execution speed and the number of steps modify the duration of the APA and the value of the CoP peaks. Step length variations influenced only the CoP peaks' values. It is interesting to note how varying the reaction time, adding cognitive tasks and performing the task with eyes closed has led to a decrease in duration and time-to-peak and an increase in ML and AP peaks.

1 GAIT/STEP INITIATION

1.1 THE DEFINITION

(Eric Yiou et al.)[1]

Gait/step initiation refers to the transient period between the quiet standing posture and steady state walking. During quiet standing, stability requires that the vertical projection of the centre of mass falls within the base of support (Figure 1). The centre of mass (CoM) corresponds to the point where the mass of the whole body is concentrated. It is the point of application of the gravity force vector. In standing posture, the base of support (BoS) refers to the area that includes every point of contact that the feet (or the foot) make(s) with the supporting surface. When one lifts the foot from the ground to step in the desired direction, balance is potentially challenged along the mediolateral direction because the base of support width in this direction is drastically reduced. If the centre of mass is not repositioned above the new base of support, a mediolateral gap between the centre of mass and the centre of pressure will be created. The centre of pressure (CoP) corresponds to the centroid of the ground reaction forces. Because of the mediolateral gap between the centre of pressure and centre of mass, the whole body will fall towards the swing leg side during the unipodal (or "execution") phase of gait initiation. The amplitude of this mediolateral fall can be estimated from the centre of mass displacement and velocity at the time of swing foot contact, *i.e.*, the greater these two quantities, the larger the mediolateral fall.

1.2 THE RELEVANCE OF THE TOPIC

(Eric Yiou et al.)[1]

Gait/step initiation is a functional task that is classically used in the literature to investigate how the central nervous system (CNS) controls balance during a whole-body movement involving change in the base of support dimensions and centre of mass progression. Gait initiation is known to be a highly challenging task for the balance control system. Indeed, it requires the integration of multiple sensory information arising from somatosensory, vestibular and visual systems, along with the coordination of multiple skeletal muscles distributed over the whole body. As such, it may potentially expose populations with sensory or motor deficits or disorders to the risk of fall.[1]

Understanding how the CNS in able-bodied subjects controls balance during gait initiation is a pre-requisite to identifying motor disorders in populations with specific impairments of the postural system, such as the elderly or patients with neurological/orthopedics conditions. It may also provide the clinicians with objective measures to assess the efficiency of rehabilitation programs and to better target interventions according to individual impairments.

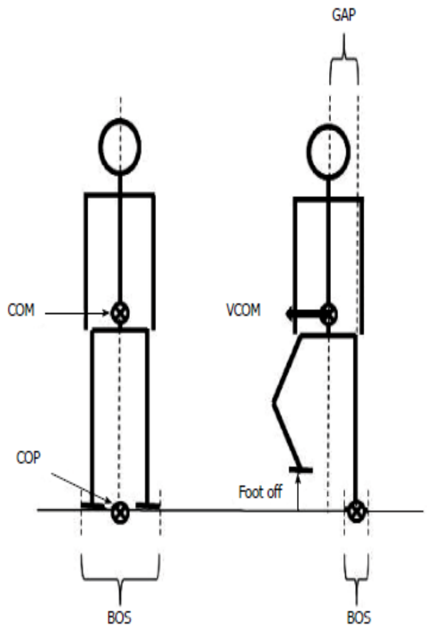


Figure 1. Representation of selected basic notions for balance analysis in biomechanics. *During the quiet standing posture, the vertical projection of the COM (Centre of Mass) onto the ground falls on the COP (Centre of Pressure). When the subject lifts the foot to step forward, the base of support size is drastically reduced. A gap between the COP and the COM may then occur, thus causing a disequilibrium towards the stance leg. BOS: Base of support; VCOM: COM velocity.*

2 STABILIZING MECHANISMS INVOLVED IN GAIT INITIATION

(Eric Yiou et al.)[1]

An attenuation of this mediolateral fall may theoretically occur during the execution phase of gait initiation *via* an action on the stance leg stiffness and the swing foot landing. Swing foot landing indeed acts to provide an immediate enlargement of the base of support size so that the centre of pressure may then be shifted laterally beyond the centre of mass and thus create a counterbalancing torque oriented toward the stance leg side. Deficits in the capacity to overcome the mediolateral perturbation to balance due to gravity force is thus thought to be of major importance in the aetiology of falls in frail populations.

Besides mediolateral instability, it is well known that the collision of the swing foot with the ground generates a large peak vertical ground reaction force. The amplitude of this peak may reach approximately twice body weight during barefoot walking at maximal speed.

Knee joint mobility (flexion) *post* swing foot contact is known to play an important role in damping these vertical ground reaction forces.

Mechanisms other than swing leg knee flexion are also developed in anticipation of swing foot contact. They are called anticipatory postural adjustments. These mechanisms act in combination to attenuate these disturbing forces and thus avoid body collapse on the ground. As such, they also contribute to maintaining stability.

To summarize, balance is disturbed during gait initiation because the act of lifting the swing foot from the ground induces a gap between the centre of mass and the centre of pressure. This gap is responsible for generating body disequilibrium and a fall towards the swing leg side. In addition, the collision of the swing foot with the ground generates a peak vertical ground reaction force, which is transmitted from swing foot to the whole body *via* bones and soft tissues. These perturbations may be responsible of falls if not properly counterbalanced.

2.1 ANTICIPATORY POSTURAL ADJUSTMENTS (APAS)

Gait initiation is classically divided in three successive phases:

1. A postural phase which precedes the swing heel off (this phase corresponds to the so-called anticipatory postural adjustments, APAs) followed by
2. the foot lift phase that ends at the time of swing toe clearance (the mass of the body is transferred to the stance leg during this phase), and
3. an execution phase that ends at the time of swing foot contact with the supporting surface (Figures 2 and 3).

It is now well established that dynamical and electromyographical phenomena are developed during APAs. Their functional role depends on the axis considered.

APAs along the anteroposterior axis are predictive of motor performance while APAs along the mediolateral axis are predictive of postural stability. Along the anteroposterior axis, APAs include a backward centre of pressure shift which promotes the initial forward propulsive forces (prior to toe off) required to reach the intended motor performance, in terms of step length and progression velocity. The anticipatory backward centre of pressure shift is due to bilateral inhibition of the ankle plantar-flexors activity followed by activation of ankle dorsi-flexors. Along the mediolateral axis, APAs include centre of pressure shift toward the swing leg which promotes centre of mass shift in the opposite direction, *i.e.*, towards the stance leg (Figure 3). These mediolateral APAs thus reduce the gap between the centre of mass and the centre of pressure at the foot off time. This gap reduction attenuates the mediolateral fall of the centre of mass toward the swing leg during the execution phase due to gravity.

The anticipatory mediolateral centre of pressure shift has been classically attributed to the loading of the swing leg associated with the activation of swing leg hip adductors.

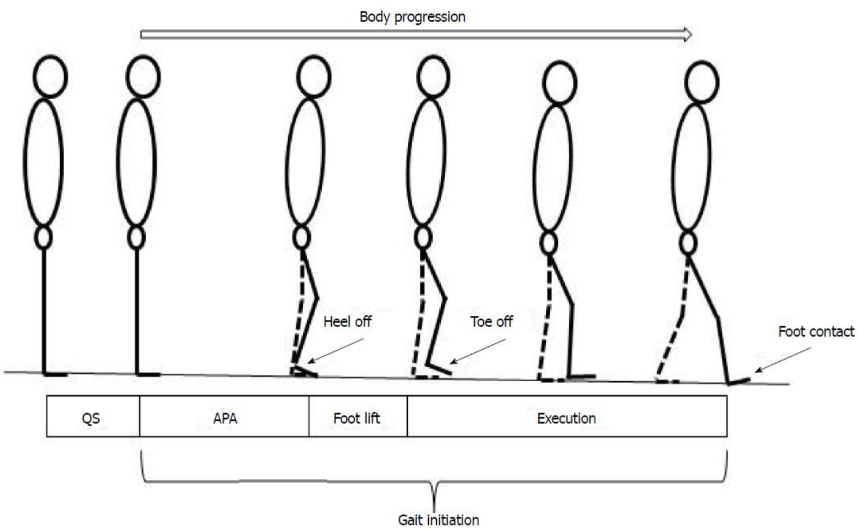


Figure 2. *Stick representation of the different phases and temporal events of gait initiation*

Recent studies further reported that, the stance knee and hip are slightly flexed during APAs, which acts to unload the ipsilateral leg and therefore complement the action of swing hip abductors. EMG analysis revealed that the flexion of the stance knee is favored by bilateral soleus silencing and a greater ipsilateral tibialis anterior activity with respect to contralateral activity, while stance hip flexion was associated with activation of the stance rectus femoris. It is to note that, due to biomechanical constraints, initiating gait from a wider stance decreases the effectiveness of hip abductor activity and increases the reliance on stance knee flexion and *vice versa.* Deficits in this motor synergy with aging or pathology may increase the risk of imbalance.

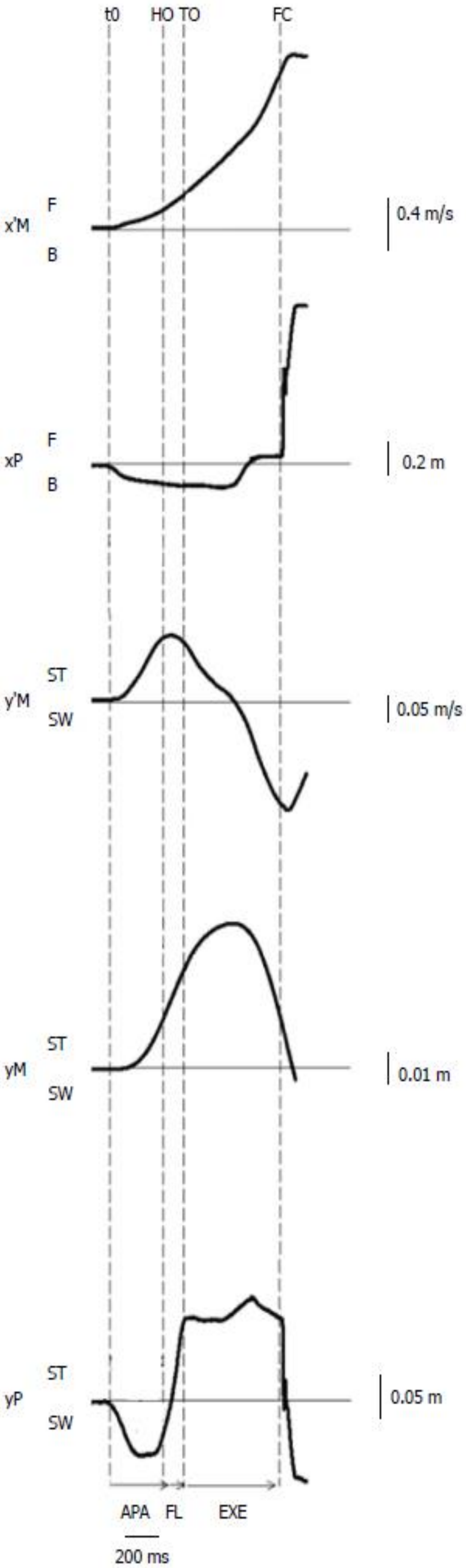


Figure 3. Example of biomechanical traces obtained for one representative subject initiating gait at a maximal velocity (one trial). *Anteroposterior direction x'M: COM velocity; xP: COP displacement; F: Forward; B: Backward. Mediolateral direction y'M: Mediolateral COM velocity; yM: Mediolateral COM displacement; yP: Mediolateral COP displacement; ST: Stance limb; SW: Swing limb. Vertical dashed lines: t0 onset variation of biomechanical traces; HO: Swing heel off; FO: Swing foot off; FC: Swing foot contact. Horizontal arrows: APA: Anticipatory postural adjustments; FL: Foot lift; EXE: Execution phase.*

2.2 STANCE LEG STIFFNESS

The results obtained in the study of Yiou E. et al., 2016 suggested that changing the stance leg stiffness during the execution phase of gait initiation has the potential to influence the amplitude of the mediolateral fall of the center of mass. Stance leg stiffness can be theoretically modified by changing the co-activation level of agonistic/antagonistic pairs of muscles crossing the ankle, knee or hip joints.

Whether the CNS uses this theoretical leg stiffness tuning strategy in combination with mediolateral APAs in order to attenuate the fall of the center of mass during gait initiation, and whether the use of this strategy depends on the sensorimotor state of the postural system remain unanswered.

Interestingly, an increase in leg stiffness is commonly found in many neurological patients such as patients with Parkinson's disease, multiple sclerosis, stroke, *etc*. It can be speculated that part of the unstable state that is classically observed in these populations during gait initiation can be ascribed to an increase in stance leg stiffness.

2.3 FOOT PLACEMENT

The action of repositioning the swing foot onto the ground allows enlarging the base of support and opens the possibility of displacing laterally the center of pressure beyond the center of mass. In this way, it becomes possible to create a mediolateral gap between the CoM and the CoP that will brake the lateral body fall and accelerate the center of mass in the direction of the stance leg (Figure 5). Foot placement would be mainly adjusted by the activity of the hip abductors of the swing limb in response to the mechanical state of the body, in terms of center of mass position and velocity.

Caderby et al.[2] have investigated the effect of the progression velocity on the mediolateral stability control during gait initiation. These authors noted that when participants initiate gait at high speed, the lateral fall of the center of mass toward the swing limb during step execution was increased compared with gait initiation performed at low and normal speeds. Nevertheless, it was observed that the participants were able to compensate this higher mediolateral instability in the high speed condition by enlarging the step width (*i.e.*, the base of support) such that the mediolateral dynamic stability at the time of foot contact remained unchanged. These findings underlined that healthy young adults were able to finely tune the mediolateral foot placement such as to maintain an invariant mediolateral stability during gait initiation.

2.4 LATERAL ANKLE STRATEGY

It is worth noting that small errors in the foot placement may be corrected even after foot landing. Indeed, after the swing foot is positioned onto the ground, it remains possible to adjust the mediolateral position of the center of pressure located beneath this foot (Figure 5). This mechanism, called “lateral ankle strategy”, would be mainly controlled by the ankle inversor/eversor muscles of the supporting foot.

Although the extent of the corrections achievable by this mechanism is small, as it is limited by the width of the foot, it allows a fine-tuning of the torque induced by the mediolateral gap between the center of pressure and the center of mass that acts to brake the lateral fall of the body.

Lateral swing foot placement and lateral ankle strategy may complement the mediolateral APAs and stance leg stiffness regulation to stabilize the whole-body in the frontal plane.

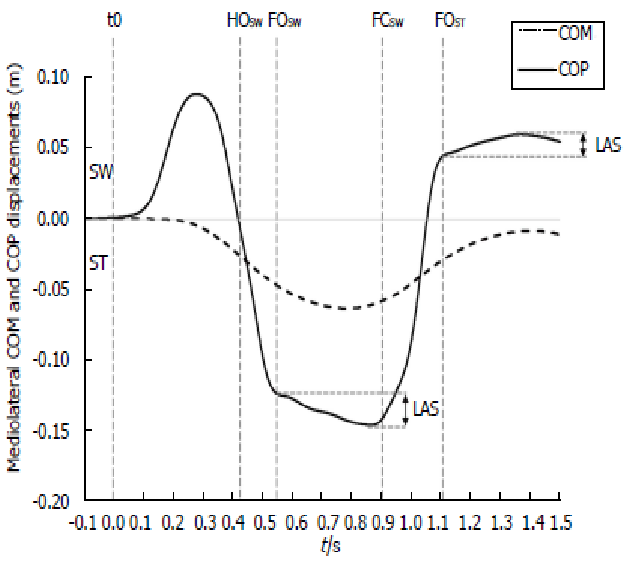


Figure 5: Typical time course of the center of mass and the center of pressure along the mediolateral direction during gait initiation. *The traces were obtained for one subject initiating gait at self-selected speed. SW and ST indicate swing limb and stance limb, respectively. t0, HOSW, FOSW, FCSW, FOST: Onset variation of biomechanical traces, swing heel-off, swing foot off, swing foot contact, stance foot off, respectively. LAS indicates “lateral ankle strategy”. The extent of the corrections achievable by this strategy may be appreciated by the difference between both the initial and the maximum lateral positions of the COP during the single support phase. COM: Center of mass; COP: Center of pressure.*

2.5 VERTICAL CENTER OF MASS BRAKING

During the execution phase of gait initiation, the backward CoP shift that is generated during APAs propels the center of mass away from the base of support. The distance between the CoM and the CoP allows gravity to generate a disequilibrium torque which accelerates the center of gravity in both the anterior and downward directions. Consequently, the lowest center of mass position throughout gait initiation is measured at the instant of foot contact. Nonetheless, in healthy adults, the center of mass velocity reaches a maximum absolute value around mid-single stance and then is decreased (Figure 6). This center of mass vertical deceleration has been shown to result from the increase in *triceps surae* activity that occurs during the second half of the execution phase of gait initiation. Difficulties to perform this active vertical braking, as observed in patients with progressive supranuclear palsy and with Parkinson disease as well as in elderly people, may induce postural instability.

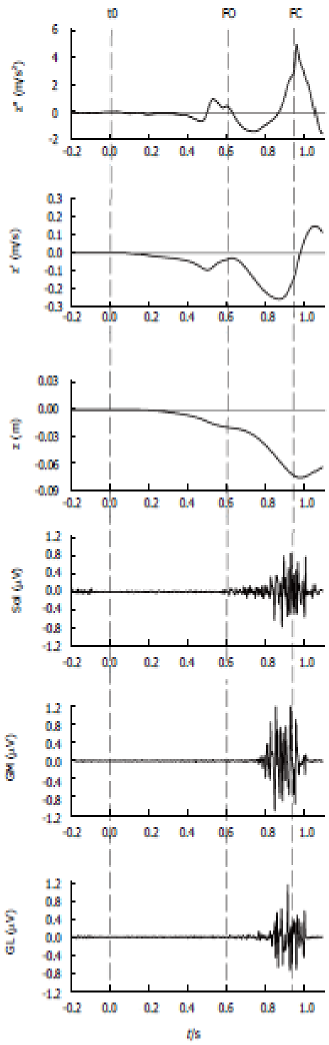


Figure 6. Vertical braking of center of mass during gait initiation. *This figure shows, from top to bottom, the timelines of the COM vertical acceleration (z''), COM vertical velocity (z'), COM vertical position (z) as well as the electromyographical activity of stance leg triceps surae activity, i.e., soleus (Sol), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) of a single recording during gait initiation. The dashed lines indicate the instants of initiation (t0), foot off (FO) and foot contact (FC). As can be seen in the figure, step execution is accompanied by a downward (negative) COM acceleration. During mid-single stance, triceps surae activity counteracts gravity and brakes the vertical fall of COM. The braking action of COM is observable as a positive acceleration (top panel) which causes the vertical absolute velocity at foot contact to be lower than the peak absolute velocity measured in mid-single stance. COM: Center of mass.*

2.6 SWING FOOT STRIKE PATTERN

During locomotion, it is known that the collision of the swing foot with the ground can occur in three ways:

- A rear foot strike, in which the heel lands first;
- a mid-foot strike, in which the heel and ball of the foot land simultaneously; and
- a fore foot strike, in which the ball of the foot lands before the heel comes down.

The swing foot strike pattern used by participants during locomotion influences the damping of the ground impact force. Swing foot strike pattern may be combined with active vertical braking of the center of mass to attenuate the potentially damaging effects of the collision forces generated at the time of foot contact.

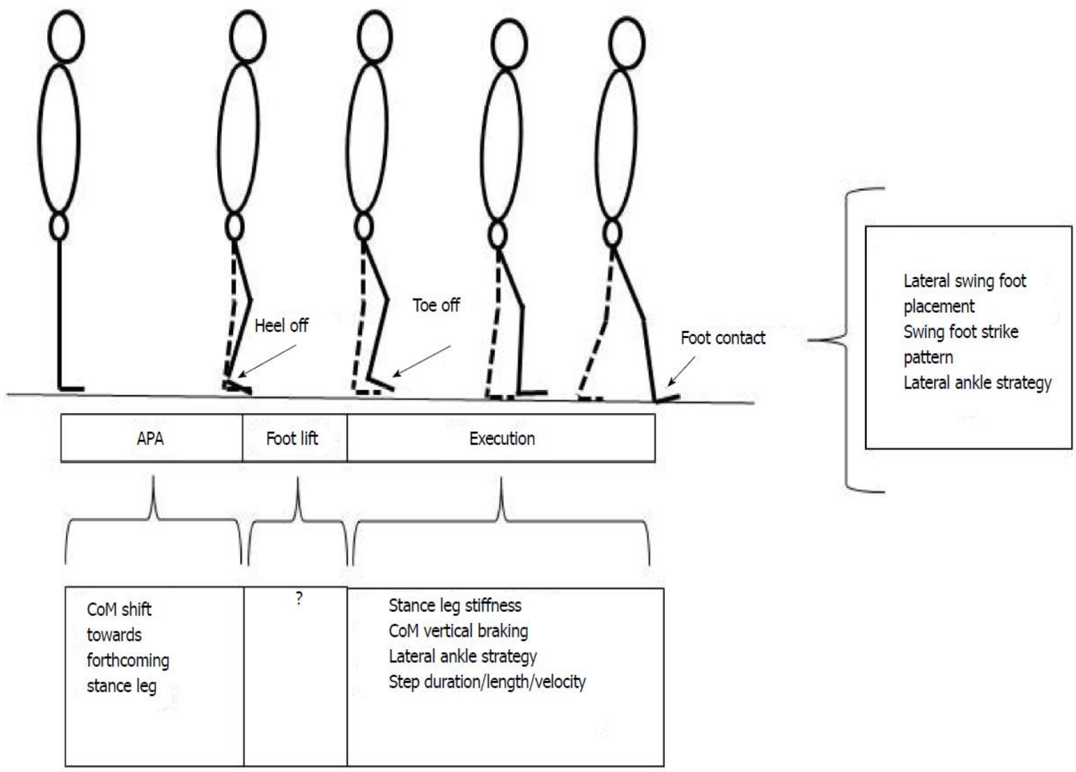


Figure 7. Synthesis of balance control mechanisms into play during gait initiation.

Now, the question on how these different balance control mechanisms are coordinated to ensure the regulation of dynamic stability remains to be clarified. Specifically, to what extent these mechanisms are complementary and may substitute to each other in case of motor deficiency should be investigated in future studies.

3 NEUROLOGICAL ASPECTS OF ANTICIPATORY POSTURAL ADJUSTMENT PRIOR TO STEPPING

Several brain structures including the brainstem, the cerebellum and the frontal cortico-basal ganglia network, with the primary and premotor areas have been shown to participate in the functional organization of gait initiation and postural control in humans, but their respective roles remain poorly understood.

In the following chapter some of the main experiments carried out will be briefly presented in order to determine the roles of the various neural components involved in the control of step initiation.

3.1 THE ROLE OF THE CORTEX

Clinical studies that examined the location of brain damage and impairment of APAs associated with step initiation suggested a potential role for premotor cortex, supplementary motor area (SMA), and primary motor cortex (M1) in the generation and execution of APA.

MacKinnon et al., 2007[3]

This study used a startle-like acoustic stimulus (SAS) and transcranial magnetic stimulation (TMS) to examine the APAs before forward stepping. The coil was

positioned over the midline about 2 cm posterior of the vertex of the scalp and oriented with the handle of the coil directed posteriorly. They also used force plates to measure ground reactions and electromyography to measure muscle activity.

After an instructed delay period, subjects initiated forward steps in reaction to a visual "go" cue. The results indicate that there was an initial phase of movement preparation during which the APA-stepping sequence was progressively assembled, and that this early preparation did not involve the corticomotor pathways activated by TMS. The subsequent increase in corticomotor excitability between the imperative stimulus and onset of the APA suggests that corticospinal pathways contribute to the voluntary initiation of the prepared APA-stepping sequence. These findings are consistent with a feedforward mode of neural control whereby the motor sequence, including the associated postural adjustments, is prepared before voluntary movement.

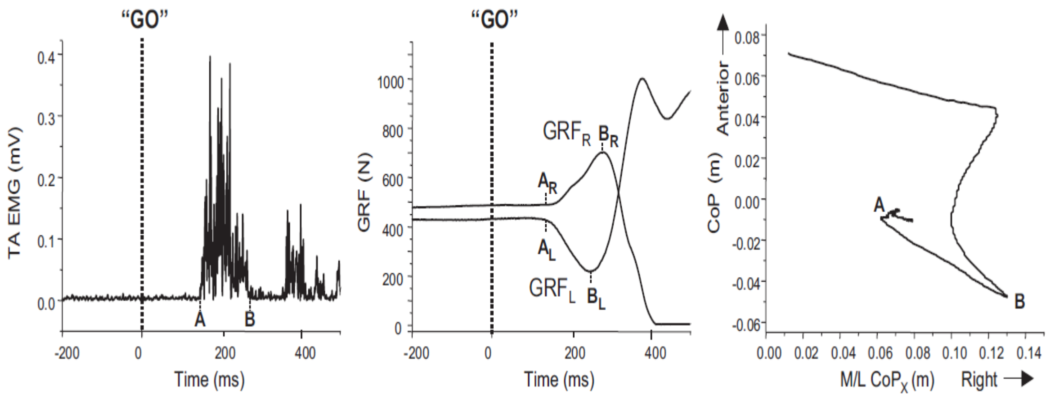


Figure 9. *Examples of the anticipatory postural adjustment (APA) parameters measured during right-step initiation. Onset, duration, and magnitude of the tibialis anterior (TA) electromyogram (EMG) burst was quantified from the start (A) to the end (B) of the initial burst. Onset, time-to-peak change, and magnitude of change in the right and left vertical ground reaction force (GRF) were measured from the start to the peak of the loading (AR to BR) and unloading (AL to BL) of the right and left legs, respectively. Onset, time-to-peak change, and magnitude of change in the medial/lateral (M/L) and anterior/posterior (A/P) net centre of pressure (CoP) were measured from the start (A) to the peak (B) of the posterior and rightward excursions of the CoP.*

J. P. Varghese et al., 2016[4]

The present study advances the understanding of the cortical involvement in the control of anticipatory balance control. The objective of this study was to isolate cortical activity related to the preparation of an APA.

An additional objective was to determine if observed APA-related cortical activity was unique to the performance of a movement as part of an APA or, rather, was comparable to execution of the same movement as part of a focal task.

In this study force plates and EEG have been used to measure respectively ground reactions and cortical signals.

Participants performed the following three motor tasks in response to an auditory cue:

1. equal-weighted lateral stepping (stepping preceded by APA),
2. unloaded lateral stepping (stepping with no APA) and
3. lateral weight shift (APA-like movement without the subsequent step)

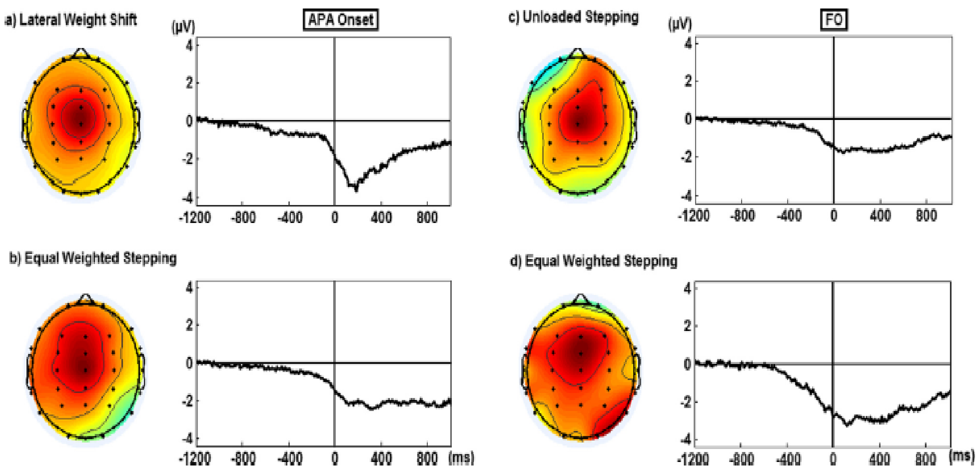


Figure 10. MRP-related ICs. Scalp maps (left frame) and time course of activity (right frame) of the independent components that contributed maximum power to the MRPs related to APA (0 ms denotes the onset of APA) during lateral weight shift (a) and equal-weighted stepping (b). Scalp maps (left frame) and time course of activity (right frame) of the independent components that contributed maximum power to the MRPs related to FO (0 ms denotes the onset of FO) during equal-weighted

EEG analysis revealed that there were distinct movement related potentials (MRPs) with concurrent event-related desynchronization (ERD) of mu and beta rhythms prior to the onset of APA and to the onset of foot-off during lateral stepping in the fronto-central cortical areas. Also, the MRPs and ERD prior to the onset of APA and onset of lateral weight shift were not significantly different suggesting the comparable cortical activations for the generation of postural and focal movements. The present study reveals the occurrence of cortical activation prior to the execution of an APA that precedes a step. Importantly, this cortical activity appears independent of the context of the movement.

3.1.1 Premotor Cortex

Chang et al., 2010 [5]

The purpose of this study was to investigate whether premotor cortex (PMC) lesions influence stepping leg selection and stepping-related APAs in patients with a PMC lesion following a stroke.

PMC plays an important role in selecting and preparing for movement.

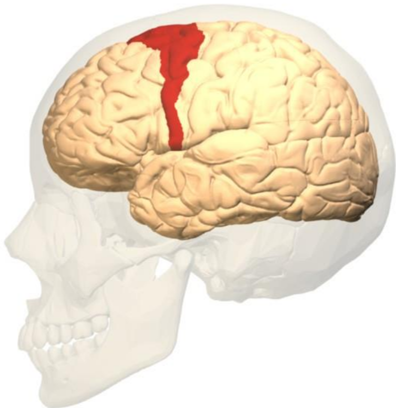


Figure 11. The premotor cortex

The neuronal activity of the PMC has been found to be direction related, magnitude-related, and time-locked to the intended movement. These characteristics of PMC neuronal activity are like those of anticipatory postural adjustments (APAs), as both relate to an intended voluntary movement.

In order to find out how the PMC cooperates during the APAs they used:

- two force plates,
- an eight-channel surface EMG system and
- a footswitch was attached beneath the mid-calcaneus of each foot to detect the heel lift-off instant of the stepping leg.

The subjects performed rapid forward stepping with the right or left leg under simple and choice reaction time conditions. This task requires intricate coordination between postural preparation and movement initiation.

This study suggests that the PMC may be involved in stepping specific APAs in humans and that a lesion in one PMC delays the contraction latency of the primary postural muscles of both lower extremities. However, because of the small sample size of this study, these findings should be tested further with a larger sample of subjects

3.1.2 Supplementary Motor Area

J. V. Jacobs et al.,2009[6]

The supplementary motor area (SMA), however, represents a potential locus of control for generating the APA. In general, the SMA contributes to generating self-initiated, multi-segmental voluntary movements (Nachev et al., 2008).

The study was carried out both on healthy subjects and on subjects with Parkinson's disease in order to determine whether SMA is an area affected by PD.

To determine the role of the SMA during step initiation they selectively disrupted the SMA with sub-threshold, 1-Hz repetitive transcranial magnetic stimulation (rTMS) and evaluated the effects of the stimulation on the APA.

They also applied rTMS over the dorsolateral premotor cortex (dlPMC) as a control site because it is not hypothesized to be involved in the control of APAs during self-initiated movement.

The results support a neural control model for voluntary step initiation in which the SMA coordinates the timing of the APA, independent of control on APA amplitude.

In addition, patients with PD likely exhibit abnormal APA timing due to dysfunction of the SMA, whereas diminished APA amplitudes may be a result of pathology to other affected regions such as the primary motor cortex or the basal ganglia.

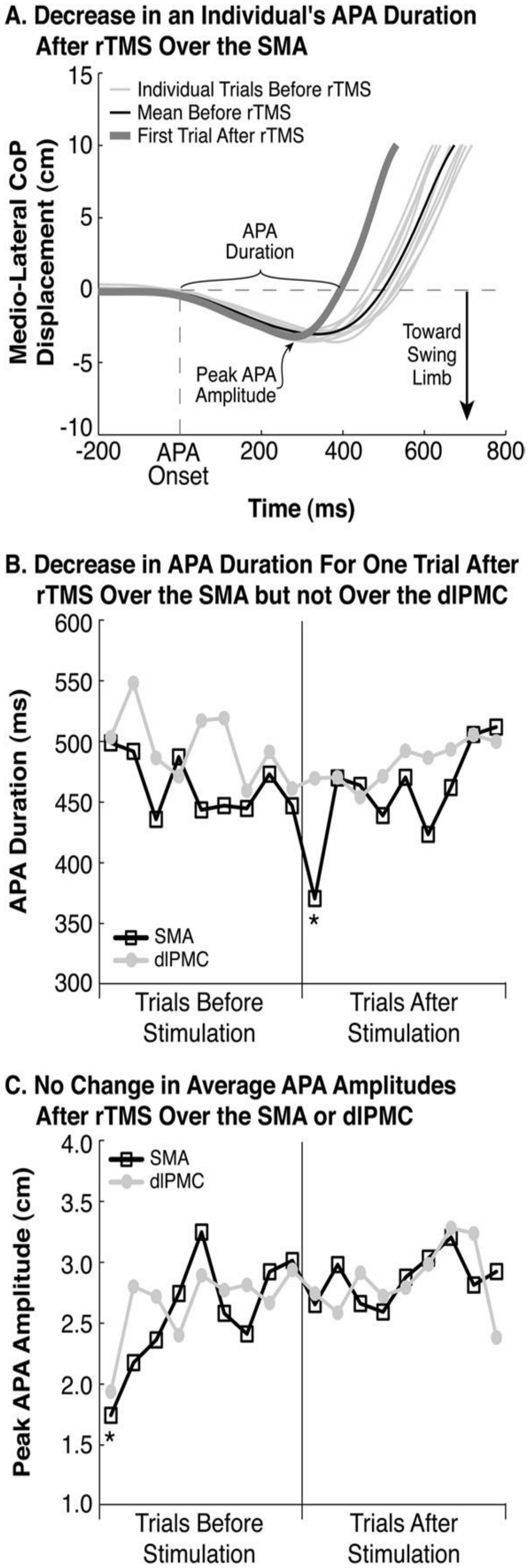


Figure 13. Effects of rTMS on the APA.

(A) An example of shortened APA duration for one trial after rTMS over the SMA from an individual with PD. The horizontal axis represents time relative to APA onset, and the vertical axis represents the lateral displacement of the CoP for individual trials before stimulation (the thin gray curves), the average of trials before stimulation (the thin black curve), and for the first trial after SMA stimulation (the thick gray curve). Negative displacements are directed toward the participant's swing limb.

(B) Average APA durations by trial for all participants, demonstrating how APA durations decreased for only one trial after SMA stimulation; no group effects were evident. The black line with squares represents the mean APA durations from the session of rTMS over the SMA; the gray line with circles, the session of rTMS over the dlPMC. The asterisk highlights the first trial after rTMS because this trial was significantly different from others.

(C) Average peak APA amplitudes by trial for all participants, demonstrating how APA amplitudes were smallest for the sessions' first trials compared to subsequent trials (asterisk); no significant changes following rTMS and no group effects were evident.

Aliénor Richard et al.,2017 [7]

In order to provide a more detailed understanding of how the cortico (SMA)-pontine-cerebello-thalamo-cortical pathway contributes to the preparation and the execution of the first step in humans, this study selectively disrupted the SMA and the cerebellum with continuous theta burst repetitive transcranial magnetic stimulation (cTBS) and evaluated the effects of the stimulation on the APAs and execution phases of gait initiation.

The results support distinct roles for the SMA and the lateral posterior cerebellum in human gait initiation, with the SMA coding for the timing, and probably amplitude, of the preparatory phase of the gait initiation, and the posterior cerebellum contributing to the inter- and intra-limb muscle coordination, and probably coupling between the APAs and the execution phases.

3.2 Cerebellum

Timmann and Horak, 2001 [8]

This study examined whether anticipatory postural adjustments were impaired in cerebellar subjects during perturbed and unperturbed step initiation. The instruments used are: two force plates that move backward together under the control of a hydraulic servomotor, and sEMG.

There were two step conditions:

1. Step to cue:
   Subjects were instructed to take a forward step with the right foot, as soon as they felt the plate begin to move and continue the step through with the left foot.
2. Step to perturbation:
   Subjects were instructed to step forward in response to three amplitudes of backward surface translations (3 cm, 6 cm and 12 cm), which were presented serially and then randomly.

The results showed that coordination of voluntary step initiation and many types of adaptive changes to voluntary steps initiated in response to perturbations appeared to be preserved in subjects with cerebellar disorders. Deficits in force production and step length were likely due to compensatory slowing in chronic cerebellar subjects. Although use of online sensory adaptation was preserved, use of amplitude prediction to modify step initiation in perturbed stepping appeared to be impaired in cerebellar subjects. Overall, the role of the cerebellum in the control of automatic postural control (e.g., anticipatory postural adjustments and automatic postural responses) appears to be limited.

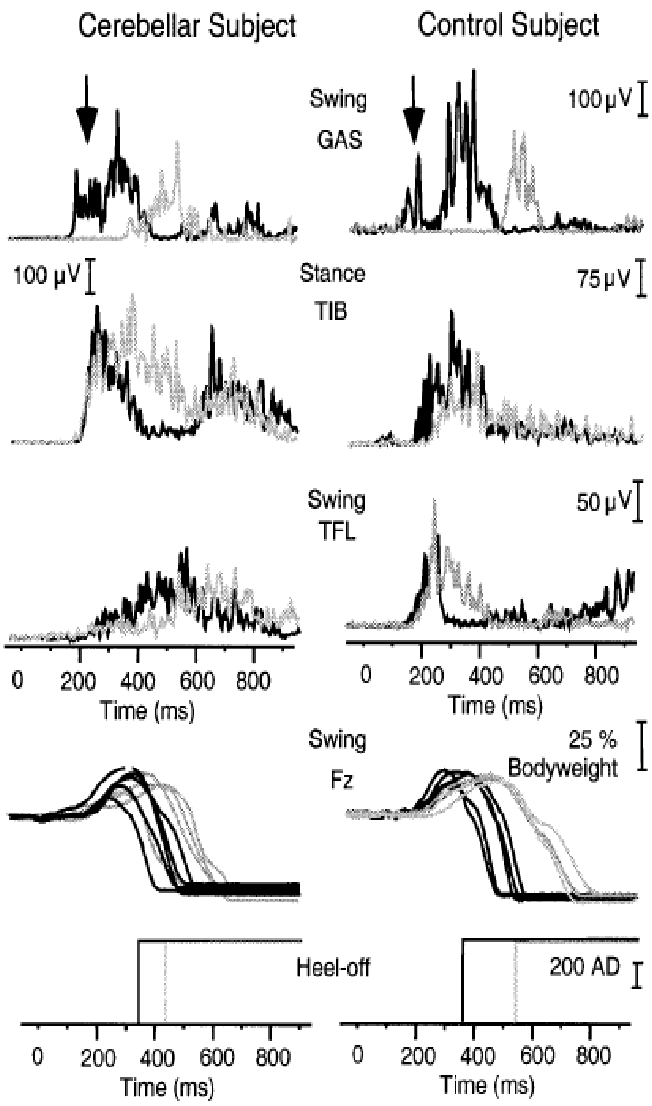


Figure 15. *Examples of representative EMG and force traces for a control and cerebellar subject for Step to Cue (light grey) and Step to Perturbation (black) conditions. GAS bursts for heel-off are preceded by automatic postural responses (arrows) in the Step to Perturbation condition. The two bottom traces show peak vertical forces (Fz) and recordings of the heel-switch. Note decreased onsets of GAS heel-off burst (top trace) and time of heel-off (bottom trace) in the Step to Perturbation condition compared to Step to Cue in both the control and cerebellar subject. Both the control and cerebellar subject showed a tendency to increase early muscle activity for gastrocnemius (GAS), tibialis (TIB) and tensor fasciae latae (TFL) and of the peak vertical forces (Fz) in the Step to Perturbation condition, whereas onset of TIB, TFL and Fz decreased in the control but not in the cerebellar subject. EMG and heel-off traces represent averages of the first five steps out of a total of ten steps in the Step to Cue condition and of the five steps in the 6-cm amplitude, random Step to Perturbation condition. Swing Fz data represent individual traces of each of the five steps. Zero ms indicates the onset of the platform movement (cue or perturbation).*

4 THE STATE OF THE ART OF EXPERIMENTAL PROTOCOLS

The chapter explains all the information gathered during the preparation of the experimental protocol.

The table below collects some of the main experiments concerning the state of the art of anticipatory movements. In order to have a broader and more complete view, the table also includes studies concerning preparatory movements prior multiple task: not only step or walking. To each line corresponds an experiment and the columns have been divided according to the following topics:

- Types of subjects analysed
- Instrumentation used during the experiment
- Experimental procedure (experimental setup, highlighting whether the controller has given instructions)
- Analysed parameters

What has emerged is that the studies done so far analyse the behaviour of anticipatory movements with respect to one or two variables. In this way there are no studies that show a comparison between the effects of each variable on anticipatory movements prior to stepping. For this reason, this thesis aims to characterize the anticipatory movements before the step when multiple external variables are modified.

Task	Objective	Patients	Instrumentation	Procedure: -Set up	-Instructions	Variables analyzed	
Gait Initiation	Examine APAs components across the lifespan	Healthy	Zeno Walkway: mat with 16 levels pressure sensing pad	Quiet standing Feet placed in their preferred natural stance Self-chosen time, pace, stepping leg	Cue: 'anytime' 'walk to the end of the mat'	The primary APA components measured from each trial were: (1) peak step leg loading, (2) peak stance leg unloading, (3) peak posterior excursion of the CoP and (4) peak lateral excursion of the CoP toward the step leg, along with step and stance leg toe-off times, and first step time and length	9
	Examine ankle APAs	Healthy and post-stroke	Force plate: force components and moments Electromyography: gastrocnemius medialis, soleus and tibialis anterior.	Feet at pelvis width Arms by their sides Focus on a target at eye level and 2 m away during 30s	'Stand as still as possible. Walk at self- adopted speed over 5 m walkway'	CoP fluctuation in the AP and ML. CoP displacement in AP direction was used to assess the onset of gait initiation (T0).	10
	To investigate APA during the transitional movement task of gait initiation (GI) in	Two equal groups of acutely post-concussion (CONC) and	All trials of GI were performed along a 10-m walkway. 3 Force plates	Self-selected comfortable stance on two FPs Participants stepped onto a third FP and	verbal cue -no additional info about the cue	Movement initiation= first change in ground reaction force and confirmed by CoP displacement.	11

individuals acutely following a concussion.	healthy student athletes.		continued walking unobstructed for approximately 10 m.		The CoP displacement was divided into 3 separate regions. During each phase, both the displacement and velocity of the CoP were calculated for the AP and ML direction. The stepping parameters: (i)Initial Step Length (ii)The mean initial Step Velocity	
To determine neurophysiological and biomechanical aspects of the preparatory postural adjustments during gait initiation (GI) in healthy younger and older adults	16 healthy younger and 15 healthy older adults participated in the study	EEG EMG Force plate CNV*, onset time of electromyographic activity in leading limb muscles and center of pressure (CoP) trajectory in the anticipatory phase of GI were measured.	The subjects stood barefoot and relaxed on the force platform, while eyes were open, both arms were hanged at the sides, feet were abducted at 10° and heels were separated mediolaterally by 6cm and weight was equally distributed.	Subjects were instructed to begin forward stepping with the dominant limb in response to response stimulus Subjects were given no specific instructions regarding the velocity or the length of steps to	In the EMG analysis, the purpose was to measure the onset of muscle activity. EEG analysis see document (14) In the force plate analysis two moment were analyzed: (i)the onset of CoP displacement (ii)The time interval between the onset point and the most posterolateral position of the CoP trajectory beneath the	12

				allow a behavior as natural as possible.	leading limb was defined as the anticipatory phase.	
To validate a previously developed method for the assessment of gait initiation on PD patients in OFF state with body-worn, inertial sensors.	Ten subjects with mild-to-moderate idiopathic PD and twelve healthy controls of similar age	Wearable sensors: 3 IMUs fixed with elastic bands on the trunk (L5), and on both shins Force plates	Participants stood with feet externally rotated on separate, side-by-side force plates at heel-to-heel distance of 10 cm Gait initiation trials starting with their most affected leg at comfortable pace	No cue reported	APAs quantification were calculated from 3 automatically detected time points: 1) APA onset, 2) heel-off, and 3) toe-off	13
To investigate how the APAs and step execution could be modified by cTBS over the SMA and the cerebellum in healthy subjects	Twenty-two healthy volunteers	Electromyographic (EMG) activity of the Soleus (SOL) and Tibialis anterior (TA) muscles were recorded. CoG and CoP were extracted from the force platform	Subjects, barefoot, and standing upright and motionless on a force plate were instructed to commence walking for 5 m (5–7 steps per trial) following an auditory cue. Self-paced speed. The subjects performed separate sessions in a	No data	-The onset of the APAs = the moment of the first biomechanical event (t0) with posterior and lateral CoP displacement -The end of APAs = the moment of the foot-off of the swing leg (FO1). -The APAs phase was divided in 2 distinct phases. -APAs duration.	7

				randomized order for rTMS over the SMA, cerebellum and sham stimulation.		Maximum posterior and lateral CoP displacements. -The step length, step width, execution velocity and duration of the swing and double-stance phases. -From the vertical CoG velocity: the peak negative value during the swing phase and its value at the time of foot contact. EMG -The onset, duration of each SOL and TA muscles burst and co-contraction (simultaneous SOL and TA muscles activity) were calculated.	
Step initiation	To investigate the dependence of APA for step initiation on velocity and length of the first step	Healthy	Force platform and 3 sensor nodes (dual axes accelerometer): posterior trunk and 2 on the lower limbs, laterally. Reflective marker	Barefoot Motionless Heels location fixed on the platform	The subject was asked to voluntary take two steps starting from the right foot.	The onset of the anticipatory phase for stepping was identified by the first measurable change on CoP excursion,	14

			Length of the first step was imposed with a line on the ground. There were measured 3 different length: short, normal and long. Subject performed 3 trials for each step length at their natural velocity, without receiving any specific instruction and 3 trials for each step length at their maximal velocity.		toward the backward direction and, laterally, toward the swing limb. The end of the APA was identified by the time of heel-off, detected by the reflective marker on the malleolus of the stepping foot. The APA magnitude: peak of antero-posterior CoP (CoP-AP) excursion in the backward direction during APA. Anteroposterior acceleration of the stance leg.	
To determine whether body-worn accelerometers could be used to characterize step initiation deficits in subjects with early-to-moderate, untreated PD.	Eleven iPD (no treated) and 12 healthy control subjects	Force plate 3 MTX Xsens sensors with 3-D accelerometers and 3-D gyroscopes: (i) the posterior trunk at the level of L5, near the body center of mass,	Feet externally rotated at their comfortable stance but with heel-to-heel distance fixed at 10 cm for all subjects. Initial stance position was consistent from trial-to-trial.	Not found	(1) APA duration (2) APA ML amplitude: (i) Peak ML-CoP, (ii) Peak ML-Acc. (3) APA AP amplitude: (i) Peak AP-CoP, (ii) Peak AP-Acc. Relative time-to-peak, from the onset of APAs to the	15

		(ii) lateral aspect of the right thigh, limb that took the first step, and (iii) the spinous process of C7.			instant of each peak APA, was also measured. The onset of APAs (first measurable change in CoP from baseline) The end of APAs: both the AP and ML CoP went back to their baseline values. The gyroscope determines: (i) time-to-peak angular (ii) range of motion of the thigh.	
To examine the preparation of APAs before forward stepping.	Ten healthy subjects ranging in age from 20 to 40 years	transcranial magnetic stimulation (TMS) Ground reaction forces (force plate) and electromyographic activity (EMG) were recorded (right tibialis anterior (TA), soleus (SOL), and sternocleidomastoid (SCM) muscles).	Subjects stood on two separate force platforms with their feet placed a natural and comfortable distance apart. Subjects took a minimum of two steps forward in response to the “go” cue. A pre-cue light was presented for 100 MS	Subjects were instructed to initiate walking “as quickly as possible” in response to the “go” cue but not to initiate the step before the cue.	onset and offset times of EMG activity in TA and SCM relative to the “go” or acoustic startle stimuli onset of the posterior and rightward excursion of the CoP (leftward for left steps), onset of the increase in the right vertical GRF (ground reaction force) and decrease in left vertical GRF (opposite for left steps),	3

			that provided one of three instructions: -right-light pre-cue: get ready to step forward with your right leg; -left-light pre cue: get ready to step forward with your left leg; -center-light pre-cue: no stepping leg instruction provided		average magnitude of the rectified EMG signal during the TA and SCM bursts, peak posterior and rightward displacements (leftward for left steps) of the CoP, and the peak increase and decrease in the right and left GRFs, respectively. The peak-to-peak amplitude of the Motor-evoked potentials (MEPs) elicited by TMS in the right TA and SOL muscles	
The present study investigated the cortical activations related to the preparation and execution of APA that recede a step. This study also examined whether the preparatory cortical activations	14 healthy adults	Ground reaction forces (force plate) and electroencephalographic activity (EEG)	Participants stood barefoot with each foot on one of the two force plates with arms by their sides and eyes open. They selected a comfortable stance width and fixed their	No data	-the time points of APA and FO onset - Reaction times -The onset of unloading for equal-weighted stepping -The onset of stepping -the onset of unloading for unloaded stepping. -the peak APA amplitude	4

related to a specific movement is dependent on the context of control (postural component vs. focal component).			gaze on a cross sign placed at eye level on the wall in front of the Participants performed the following three motor tasks in response to an auditory cue: (1) equal-weighted lateral stepping (stepping preceded by APA), (2) unloaded lateral stepping (stepping with no APA) and (3) lateral weight shift (APA-like movement without the subsequent step)		The time required to unload the swing foot (unloading phase duration) for both stepping tasks -Total stepping time EEG data -MRPs related to APA and FO -the amplitude of MMP	
This study investigates how stroke-induced PMC lesions affect stepping leg selection and anticipatory postural	Fifteen hemi-paretic patients and eight age- and sex-matched healthy adults	Two force plates An eight-channel surface EMG system A foot-switch was attached beneath the mid-calcaneus of each foot to detect the	In the stepping experiment, subjects stood facing a monitor. Each foot was placed on one force plate with feet 25 cm apart and	All subjects were asked to prepare to react to an upcoming ‘‘go’’ signal	-The initial Fz patterns before the heel lift-off of the stepping leg. -The contraction latency of the bilateral TA muscles.	5

adjustments (APAs) preparation.		heel lift-off instant of the stepping leg	158 externally rotated. The monitor was raised to each subject's eye level and positioned 1.5 m in front.		-The reaction time (RT) of the stepping leg.	
To determine how the SMA specifically contributes to the generation of the APA during step initiation.	Eight participants with PD and eight participants without PD	rTMS force plate	Participants to stand with each foot on a force plate with eyes closed. The participants stood in a stance width that equaled 11% of their body height and they started with a pre-determined stepping foot. Participant did 4 different tests: Self-initiated stepping Cued stepping Forced stepping 30 s quiet stance	The participants were asked to step without cues and with their eyes closed.	-The lateral displacements of the center of pressure (CoP) from two force plates, one under each of the participants' feet. -An initial CoP position, which was defined as the average CoP position over the first 500 ms of recording. -The duration of an APA Peak APA amplitudes: the maximum lateral displacement of the CoP toward the swing limb just prior to foot-lift. -Each participant's average APA duration, the variability of each participant's APA durations, and the average	6

						peak APA amplitude prior to rTMS.	
Stand and catch a load dropped from a specific height	Examine APAs associated with a loading perturbation	Children with hemiplegic and diplegic cerebral palsy	1 unidirectional accelerometer on the dominant hand EMG: erector spinae rectus abdominis biceps femoris rectus femoris medial soleus Force Platform	Stand barefoot on a force platform. Feet placed at shoulder width. Arms outstretched in front of the body at shoulder height holding a basin	Cue: a tone (indicate the load was about to release)	EMG data: 1) baseline EMG activity while standing with the plastic basin 2) anticipatory changes in muscle activity immediately prior to the load catch CoP data: Anticipatory CoP displacement	16
Release a load held in the extended arm	To study adaptation of APAs to changes in the direction of self-initiated perturbation and an additional manual support	Subjects with hemiparesis	Force platform, miniature unidirectional accelerometer on the load EMG and Force sensor	Stand comfortably on the force platform. 4 different exercise: -with or without manual support -frontal and side direction	‘touch the support pad’ ‘Grab the load’ ‘Wait the beep’ ‘Release the load in a self-paced manner by a quick opening of the hand’	See the document 4	17

One leg stance	To investigate both the initial anticipatory phase and the subsequent unipedal balance	Subject with Parkinsonism	3 wearable inertial sensor IMU: posterior trunk left and right frontal face of the tibias	Subjects were not warned which leg to lift At the beginning of each repetition, the examiner gave a vocal instruction specifying which leg had to be lifted.	"Look straight ahead. Keep your hands on your hips. Lift your leg off the ground behind you without touching or resting your raised leg upon your other standing leg. Stay standing on one leg as long as you can."	-*T*lift = the initial raising movement of the leg. -*T*peak = the maximum absolute peak of the trunk ML acceleration preceding *T*lift. -The signal amplitude (ML-peak) was adopted as a descriptive parameter of the APAs. -*T*onset = the APA onset -ωML was used to detect the initial and final instants of unipedal balance (*T*start and *T*stop)	18
Rise to toes	To examine the influence of fear of falling or postural threat on the organization of posture and voluntary movement during a rise to toes task in healthy young adults.	12 healthy young adults	Force plate 21 infrared-emitting diodes providing an estimation of total body COM. EMG with disposable surface electrodes placed bilaterally on the TA, SO and medial GA muscles.	Participants were instructed to stand quietly on the force plate with their arms at their sides and their eyes open. Participants fixated on a target located 6m in front of them at eye level. Foot	Participants were instructed to voluntarily rise to the toes as quickly as possible following a verbal cue and	*Anticipatory postural adjustment* -Estimation of the total body CoM -the initial position of the CoP and COM -the magnitude and peak velocity of the CoP APA *Forward movement*	19

				position was traced to maintain the same initial stance position for each trial. Postural threat was modified through alterations to the surface height at which individuals stood (low or high platform) and changes in step restriction (away from or at the edge of the platform) creating four levels of postural threat: LOW AWAY, LOW EDGE, HIGH AWAY and HIGH EDGE.	maintain this new position of support over the toes for 3 s.	-The duration of the CoP APA -the magnitude and peak velocity of forward CoP movement *Centre of pressure and centre of mass* -the number of crossings of the COM by the CoP over the interval from peak backward CoP displacement to maximum displacement of the COM *Electromyography* Muscle onset latency and integrated muscle activity And other variables about *Muscle activity level etc*	
Balance control while sitting	To analyze the effects of changes in body position and changes in the	Eight healthy subjects	Force transducer A pressure sensor EMGs were recorded in the following	Subjects exerted upward or downward vertical force against an object attached to a	Verbal command "Pulls"	They used own indices for EMG activity -The vertical force applied to the can	20

	location of body supports on anticipatory postural adjustments (APAs) while sitting.		dominant-side leg and trunk muscles using pairs of disposables, self-adhesive electrodes tibialis anterior (TA), soleus (SOL), rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA) at the umbilicus level, and erector spinae (ES) at L3-4 level.	rigid frame and released the object with a fast bilateral shoulder abduction movement. All the movements were executed in a self-paced manner. While sitting, four support conditions were studied: -with and without feet support, and -with anterior or posterior lower-leg supports.			
Balance control while standing	To study the role of different leg and trunk muscle groups in the generation of APAs prior to lateral and rotational perturbations associated with	Seven healthy subjects, three males and four females	Force platform EMG Force sensor was securely attached to the wall A miniature	For Experiment1 and Experiment2 procedure see the document 10. Postural perturbations were induced by a variety of manipulations	Not found any specific instruction	- the first visible deflection of a signal from the accelerometer or of the EMG signal in the wrist flexor - integral EMG indices	21

predictable and self-triggered postural perturbations during standing.		unidirectional accelerometer was taped to the wrist of the subject	including catching and releasing a load with the right hand extended either in front of the body or to the right side, performing bilateral fast shoulder movements in different directions, and applying brief force pulses with a hand against the wall.			
To study the role of APAs in compensatory postural adjustments.	Eight healthy subjects (4 males and 4 females)	force platform EMG was recorded from the following right lower limb and trunk muscles: lateral gastrocnemius (GAS), tibialis anterior (TA), rectus femoris (RF), biceps femoris (BF), gluteus Medius (GM), external oblique (EO), rectus	Perturbations consisted of unidirectional forces applied to both the subjects' extended arms, using the pendulum that was pulled to a fixed distance away from the subjects' hands. The two experimental conditions were:	Not found any vocal instruction	-Integrals of anticipatory and compensatory EMG activity -muscle latencies -Displacements of the center of pressure (CoP) in the anterior-posterior direction -the moment in sagittal plane (My), -the vertical (Fz) and anterior–posterior (Fx) components of the ground reaction force,	22

		abdominis (RA), and erector spinae (ES). force platform accelerometer was attached to the pendulum.	1. “predictable perturbation” (eyes open) 2. ‘‘unpredictable perturbations” (eyes closed) The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart.		-the distance from the origin of the force platform to the surface The average baseline magnitude of the CoP displacement	
To investigate the relationship between APAs and CPAs from a kinetic and kinematic perspective.	Eight healthy subjects (4 males and 4 females)	Stereophotogrammetry A six-camera VICON 612 system (Oxford Metrics) was used to collect three-dimensional kinematic data. Retroreflective markers See the document 12 for positions force platform	Perturbations consisted of unidirectional forces applied to both the subjects’ extended arms, using the pendulum that was pulled to a fixed distance away from the subjects’ hands.	Not found any vocal instruction	-Displacements of the center of pressure (CoP) in the anterior–posterior direction -My is the moment in sagittal plane, -Fz and Fx are the vertical and anterior–posterior components of the ground reaction force	23

			An accelerometer was attached to the pendulum	The two experimental conditions were: 1. "predictable perturbation" (eyes open) 2. ‘‘unpredictable perturbations" (eyes closed) The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart.		-d is the distance from the origin of the force platform to the surface. -The joint angles -The COM displacements in the sagittal (COMy) and transverse planes (COMz) -The onset of COMy, COMz and CoP displacements were determined visually by a trained researcher. -The peak displacements for COMy, COMz and CoP and their respective times -the mean raw angles of ANK, KEE, HIP, SPN, TOR, and HEA for each subject in the sagittal plane.	
Reaching movement	To examine whether the expectancy of visual information about the target modifies APAs	Ten right-handed volunteers	EMG Anterior Deltoid (AD) and from two postural muscles of both lower-limbs (Tibialis Anterior, TA and Hamstring, Ham).	Ten standing subjects had to (1) move the eyes, head and arm, to reach, with both gaze and index-finger, a target of known	The instruction was to freely decide when starting the movement but, once started, to	See article	24

			EOG-Up A 3D motion analysis system	position placed outside their visual field (*Gaze-Reach*); (2) look at the target while reaching it (*Reach in Full Vision*); (3) keep the gaze away until having touched it (*Reach then Gaze*) and (4) just *Gaze without Reach* the target. Subjects stood on a force platform according to their spontaneous upright stance, while keeping both upper-limbs along the body.	reach the target as fast as possible		
Reach and touch movement from sitting posture	To investigate the influence of the Perceptive Impairment (PI) on motor control and to appraise if the PI	Twenty-four diplegic children	force platform registered the CoP trajectories accelerometer in a small ball	The subjects were asked to sit still, gazing at an eye-level fixed point, and then reinstate the same initial position of head,	No instructions reported	CoP trajectory, was divided (offline) in three different intervals: (i) the waiting interval during the first 3 s of still sitting (Wint), (ii) the APA interval (APAint) if	25

can be revealed by a reaching task.			trunk and hands during the trials. A whistle blew 3 s after the beginning of the recording, triggering the subject to reach and touch the ball.		present, and (iii) the reaching interval (Rint). The reaching performances were quantified by means of six different parameters. (1) the percentage of times the target was touched, (2) the Reaching Time (RT), (3) the Maximum Displacement (MD) of the CoP during Rint, (4) the percentage of APA onsets (%APA), (5) the Angle Error (AE), being the angle between the RD and the APA direction, (6) the APA Magnitude (M), being the maximum CoP displacement reached during APAint from the midpoint.	

4.1 Relevant variables

The previous table allowed to highlight which are the external variables that are usually taken into consideration during the experiments. The following table shows some of the possible variables that can be considered for the construction of an experimental model. The experimental model of this thesis has considered some of the ones listed below for reasons of measurement duration and laboratory availability.

Tasks that change the support base during the execution:

Gait initiation	Quantity of step	Undefined number of step
		Step initiation
		Fixed number of steps
	Velocity of the movement	Slow
		Fast
		Normal
		Self-chosen pace
	Arm position	By their sides
		Self-chosen position
	Direction of the step	Lateral
		Straight
		Backward
	The gaze	Focus on a specific target
		Focus on a self-chosen target
		No instruction given
		Eyes closed
	Presence of an obstacle	Knee height obstacle
		Ankle height obstacle
		Hole
	Length of the step	Short
		Medium
		Long
	Additional weight	In the hands
		On the shoulders
		On the legs
	Shoes	Without
		Heeled shoes
		Flat shoes
	Feet position	Self-chosen
		Position set by an external agent (pelvis width, shoulder width, others)
	Hardness of the supporting surface material	Soft
		Rigid

Size of the supporting surface	Smaller than support surface of the feet
	A little bit bigger than the feet surface
	Bigger than the feet surface
Starting time	Self-chosen time after a cue
	Start as soon as possible after the cue
Stepping leg	Dominant (chose with a test)
	A fixed one
	A self-chosen one
Stair step	Upward
	Downward
Nature of the cue	Visual
	Auditory
	Tactile

One leg stance

Hand position	
Velocity of the movement	
Additional weight	
Shoes	
Feet position	
Hardness of the supporting surface material	
Size of the supporting surface	
Starting time	
Support leg	Fixed one
	Self-chosen one
Time to stay in position	As long as you can
	A fixed period of time

Rise to toes	
	Velocity of the movement
	Additional weight
	Shoes
	Feet position
	Hardness of the supporting surface material
	Size of the supporting surface
	Starting time
	Time to stay in position
	Arm position

Get on heels	
	Velocity of the movement
	Additional weight
	Shoes
	Feet position
	Hardness of the supporting surface material
	Size of the supporting surface
	Starting time
	Time to stay in position
	Arm position

There are also tasks that allow the support base to be kept constant during their execution:

Reaching tasks	
	Velocity of the movement
	Additional weight
	Shoes
	Feet position
	Hardness of the supporting surface material
	Size of the supporting surface
	Starting time

If there is an object:	
	Object position
	Size of the object
	Object weight

5 THE OBJECTIVES

The objective of this thesis is to provide a characterization of anticipatory movements before the step. To do this, we want to propose a description of the trend of the main signs that describe these movements: the center of pressure and the acceleration of the trunk, at the height of the center of mass. This study also aims to bring a description of these signals to varying multiple variables. In order to understand how these external factors are influential in the preparatory phases prior step.

6 METHODS AND MATERIALS

6.1 SUBJECTS

Five young adults (4 men, 1 women) with no previous history of neurological disorders or equilibrium problems participated in this study. Their data are reported in the table below.

Subjects with corrected vision wore their glasses during the study.

Subjects	Age (Years)	Weight (Kg)	Height (cm)
P1	23	56	171
P2	24	90	180
P3	22	71	185
P4	24	67	182
P5	22	78,5	184
Mean	23	72,5	180,4
SD	1	12,72	5,59

6.2 TEST PROCEDURE

At the beginning of each experimental trial, subjects stood barefoot and motionless on the force platform with a self-chosen feet position. They were instructed to keep arms by their side and fix the gaze on a specific target at eye level. Heels location was fixed on the platform with an adhesive tape, to ensure accurate execution of the entire experiment. Subjects performed 3 trials for each instruction starting with their *dominant leg*. The test used by Van Melick N.[26] was used to determine the dominant leg. Every trial start with a vocal cue by the examiner: ‘go’. After positioning the subject, the examiner waited for at least 8 seconds before giving the starting signal.

This trial duration was found to be long enough to allow for minimization of the natural sway before the step. There was a 5 minutes gap between the first 7 seven tasks and the following eight tasks which was enough to prepare the equipment for the next recordings. This resting period was considered to prevent fatigue.

The subjects were asked to voluntarily perform the following tasks:

Test number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Quantity of step	Take 1 step	■			■	■	■	■	■	■	■	■	■	■	■	■
	Take 3 step		■													
	Start walking			■												
Speed	Go as fast as you can					■										
	Slowly				■											
	Normal	■	■	■			■	■	■	■	■	■	■	■	■	■
Step Direction	Lateral direction						■									
	Straight	■	■	■	■	■			■	■	■	■	■	■	■	■
	Backward							■								
Obstacle	No obstacle	■	■	■	■	■	■	■			■	■	■	■	■	■
	With an ankle height obstacle								■							
	With a 30cm height obstacle									■						
Step Length	Short step										■					
	Average length step	■	■	■	■	■	■	■	■	■			■	■	■	■
	Long step											■				
Starting time	Self-chosen	■	■	■	■	■	■	■	■	■	■	■				
	As soon as possible												■			
The gaze	Eyes closed													■		
	Focus on a specific target	■	■	■	■	■	■	■	■	■	■	■	■		■	■
Rise on toes															■	
With a cognitive task																■

Instructions

1. Take 1 step forward at normal speed
2. Take 3 step forward at normal speed
3. Start waking forward at normal speed
4. Take 1 step forward slowly
5. Take 1 step forward as fast as you can
6. Take 1 step in the lateral direction at normal speed
7. Take 1 step backward at normal speed
8. Like task 1 (the presence of an obstacle doesn't determine any instruction change)
9. Like task 1
10. Take 1 short step forward at normal speed
11. Take 1 long step forward at normal speed
12. Take 1 step forward at normal speed. Start as soon as possible after the cue.
13. Close your eyes. Take 1 step forward at normal speed.
14. Rise on toes. Take 1 step forward (after the subject has assumed a stable position)
15. Take 1 step forward (while the subject is making the cognitive task). The cognitive task we have chosen is: 'Start counting out loud from 103 backwards to 7 in 7 (103-7 = 96-7 = 89-7 =...)'.

    After 4 operation the 'go' signal was given. Any calculation errors have been reported.

The task order was determined randomly for each subject.

6.3 INSTRUMENTATION SETUP

Accelerometers

Data were collected from 3 EXL-s3 sensors, fixed with non-reflective adhesive tape. EXL-s3 sensors measure 54 x 33 x 14 mm and weigh 22 g. Some device specifications are:

- Triaxial accelerometer with selectable range (± 2 / ± 4 / ± 8 / ± 16 g)
- Triaxial gyroscope with selectable range (± 250 / ± 500 / ± 1000 / ± 2000 °/s)
- Triaxial magnetometer with range ± 1200 μT

- Sampling frequency of 100 Hz
- Bluetooth ™ 2.1 class 1
- 1 Gb NAND FLASH memory
- 3-hour lithium battery.

In this application, ranges of 8g for the accelerometer and 1000 °/s for the gyroscope were selected. Signals were sampled at 100 Hz.

One unit was attached to the lower back, around the L3-L4 vertebra. This position was chosen due to the proximity to the center of mass (CoM) of the human body.
The other two inertial sensor units were attached to the lateral side of both ankles.
The accelerometers were arranged in such a way as to have the axes corresponding to the mediolateral and anterior posterior direction.
Specifically, they were arranged as in Figure 16.

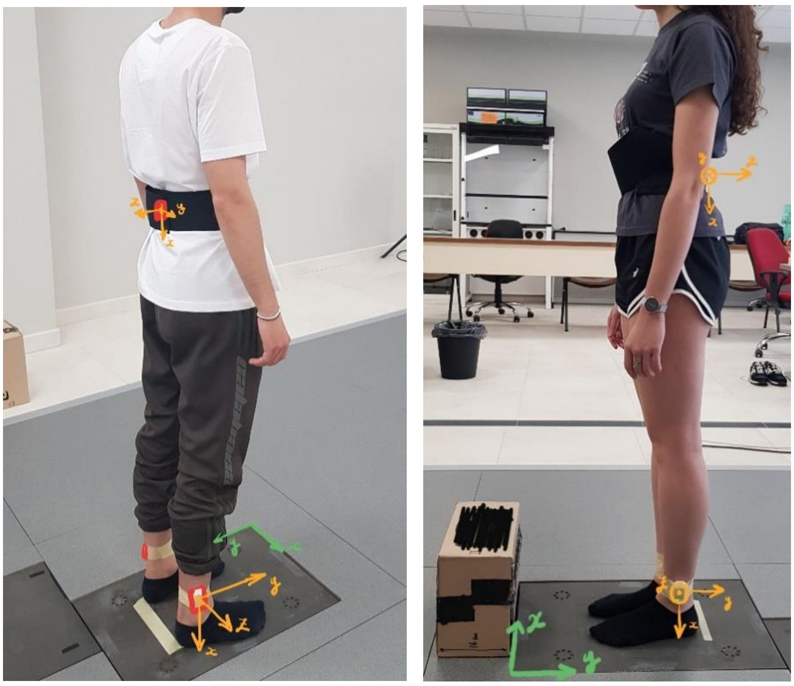


Figure 16. *The accelerometer SDRs are yellow while the platform has the*

Force plate

Ground reaction forces and center of pressure (CoP) displacement were measured via one force plate at 800 Hz.
Y and X axes correspond respectively to the anteroposterior and mediolateral direction.
The force plate used is a BERTEC, type 4060-08.

Stereophotogrammetry

This system was used to determine when the examiner gave the starting signal.
When the go was given the examiner showed the marker to the pre-installed infrared camera system. The marker signal was sampled at 200Hz.

Signals were analyzed offline using MATLAB® (Math-Works, Natick, MA).

6.4 DATA PROCESSING

6.4.1 Filtering

The data from the accelerometers were low pass filtered using eight order zero phase Butterworth filter with a cut-off frequency of 3.5 Hz.
GRF and CoP displacement were low pass filtered using fourth order zero phase Butterworth filter with a cut-off frequency of 20 Hz.

6.4.2 Synchronization

The force platform and the stereophotogrammetric system were already synchronized while the IMUs were in a separate system. Before starting a measurement, small strokes were given on the IMU positioned on the platform in order to have peaks on both signals and thus be able to synchronize them.

6.4.3 Resampling

The platform and marker position data were resampled at 100 Hz.

6.4.4 Cut and assign

To avoid making the data collection too long and tiring for the subjects, it was decided to perform one or two recordings at most during which all 15 tasks were performed by the subject.
In this way the recording must be cut and the various resulting tracks must be assigned to each individual task and to each individual test.
To do this, an algorithm was written based on the GRF perpendicular to the ground and the marker track.

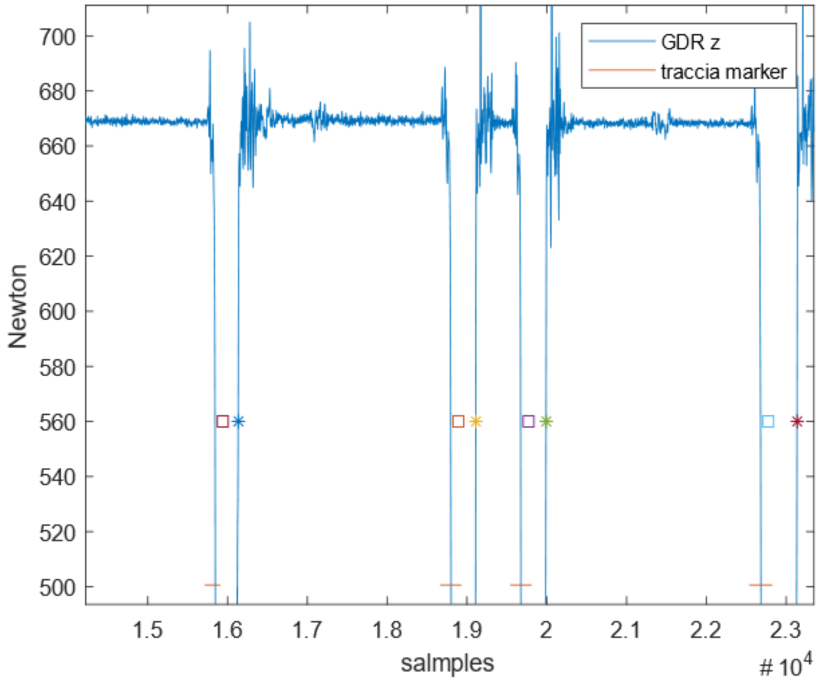


Figure 17. *The blue signal indicates the presence of the subject on the platform. The algorithm recognizes it and cuts the signal (from the asterisk to the square).*

For better management and organization, the tracks were organized in a structure called "participant". Inside it there are as many structures as there are participants (P1, P2, ... P5) and each of these contains an amount of structures equal to the tasks performed by the participant (task1, task2, ... task15). Each task has been performed three times, therefore within each "task" there are 3 additional structures (trial1, trial2 and trial3, in the structure they are called ‘try’) containing the relative traces of the force platform, marker and accelerometers.

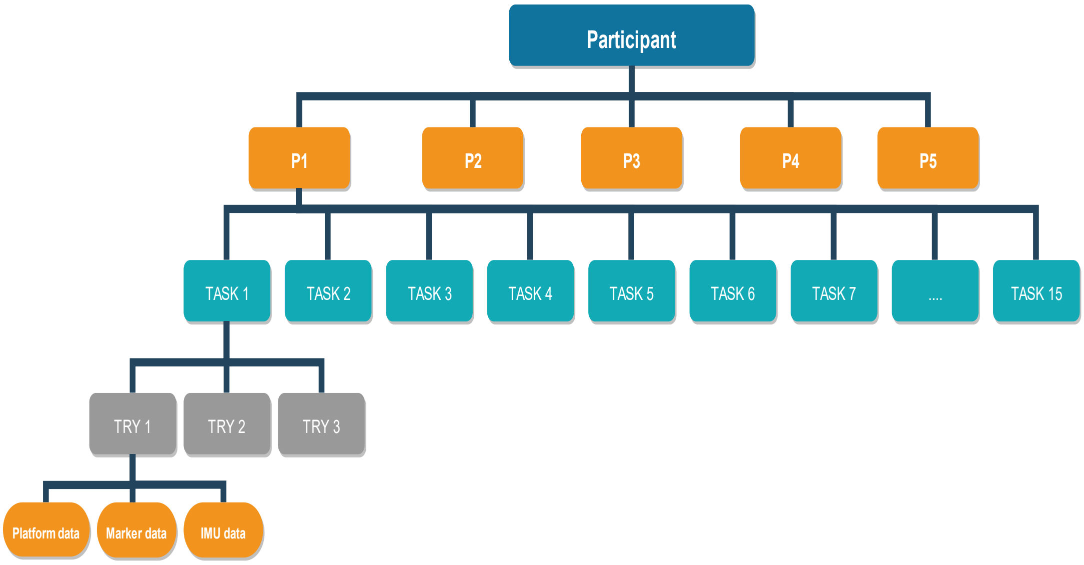


***Figure 18**: design of the structure participant*

Thanks to a similar structure, the algorithms that will be described below have been able to perform their operations iteratively, without having to manually enter the tracks for each test.

6.4.5 The Algorithm

Starting from the "participant" structure, the data corresponding to the test to be analysed are extracted. In addition to the data of the platform, the marker and the IMU on the trunk, the algorithm recognizes which is the dominant leg and consequently extracts only the data from the corresponding accelerometer.

Then it proceeds with the recognition of the instant in which the "go" is given (start), the instant in which the toe is raised (toe off) and the moment in which the subject has his dominant leg in the middle of his flight phase (mid-swing).

6.4.5.1 Start index

Il primo indice con valore non nullo della traccia del marker è stato assunto come segnale di start.

6.4.5.2 Mid-swing and Toe off index

The function used to find the mid-swing instant is based on the processing of the angular velocity measured by the accelerometer placed on the dominant leg ankle. The axis around which the angular velocity is measured is in the middle lateral direction from right to left.

The algorithm verifies that the subject is stopped in such a way as to recognize incorrect executions. To do this it is verified that the standard deviation of the 3 seconds preceding the start is less than 1.5 ° / sec.

Then the first negative peak that exceeds 50 °/sec beyond the start signal is considered as mid-swing instant. [27]

Moreover, the only positive peak between the start and mid swing is indicated as a toe-off instant.

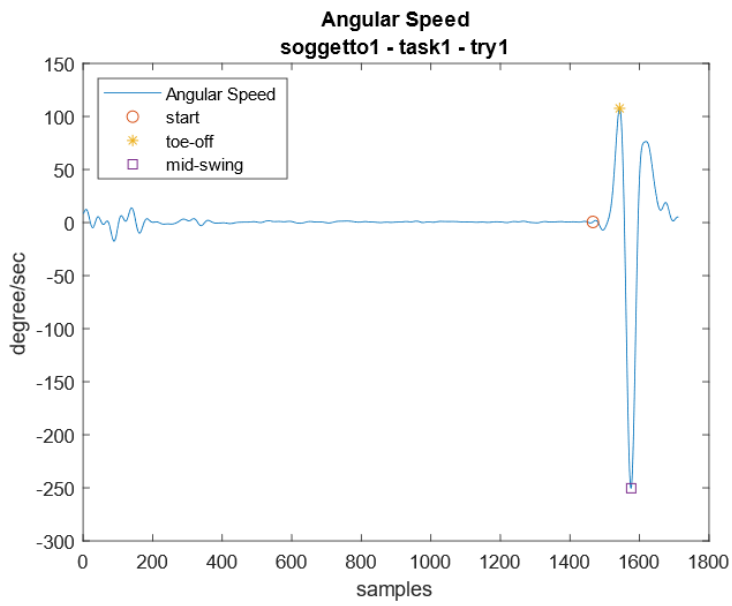


Figure 19

6.4.5.3 Processing of the centre of pressure signal

There are two functions called "APA peak AP" and "APA peak ML" which process the y and x signal of the force platform (CoP AP and CoP ML).

The functions verify that the signal has a standard deviation minor than 0.01 m. If it is not, the signal is considered unstable and therefore not suitable for analysis.

An APA peak to be recognized as such must meet the following requirements:

- have values greater than the threshold value for a duration between 0.1 and 1.5 sec;
- the peak must start after the start index
- the values must return to the baseline value before the mid-swing index

Start APA, end APA, peak value and peak duration are the function outputs.

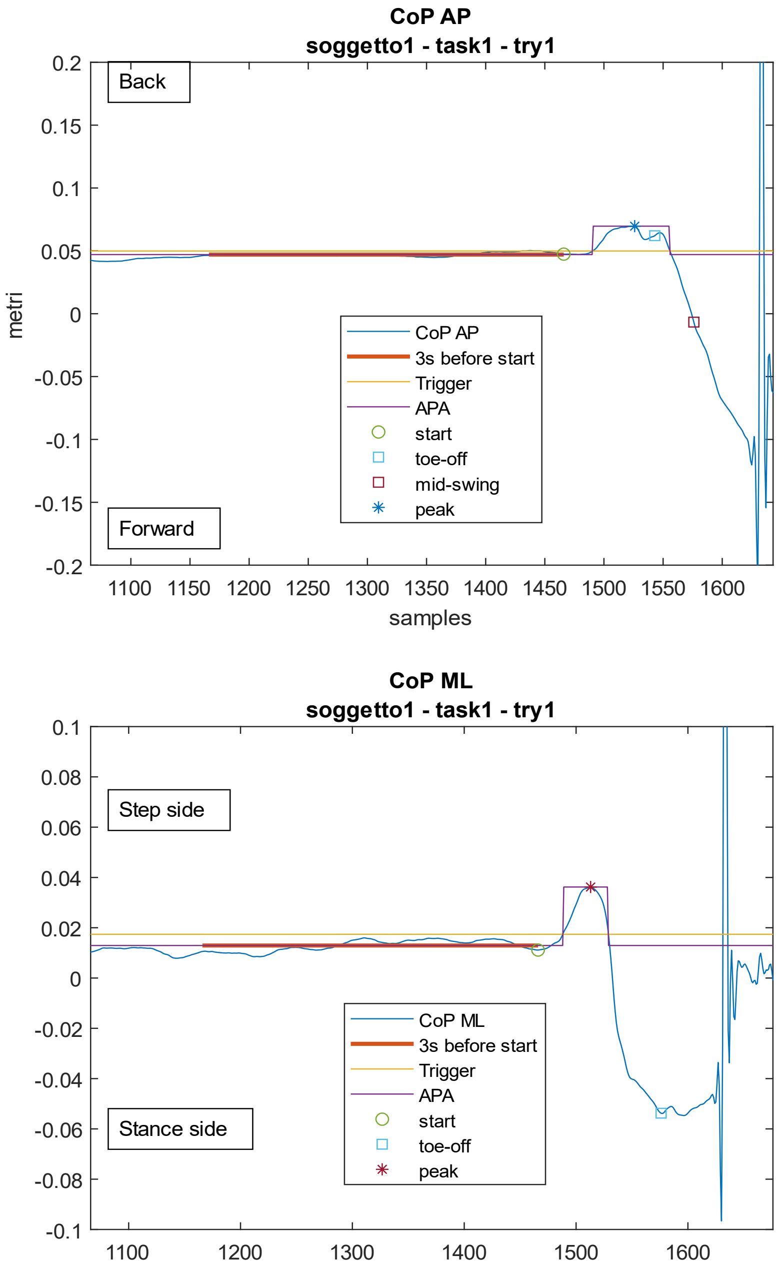


Figure 20

6.4.5.4 Processing the acceleration of the trunk

The algorithm examines both mediolateral (Acc ML) and anteroposterior (Acc AP) acceleration. If the signals in the three seconds prior to the start show a standard deviation greater than 0.1 m/s^2 they are discarded as they are considered unstable.

The algorithm detects the peaks between the start signal and the toe off moment which exceed a minimum value set at the baseline (the average value of the signal during the

3sec before the start) plus 2 standard deviations. The outputs are the value and position of the peak.

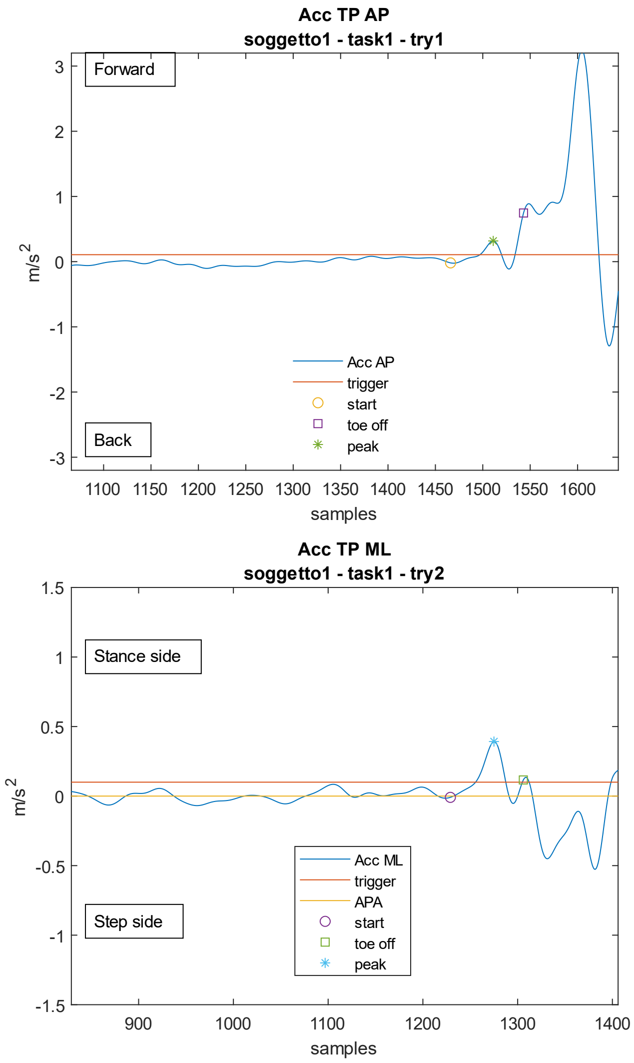


Figure 21

6.4.6 Statistical analysis

For each feature and for each task we calculated:

- the average value
- SD, it is calculated starting from the average values of the single participants
- ICC, intraclass correlation coefficient

Intraclass correlation measures the reliability of ratings or measurements for clusters — data that has been collected as groups or sorted into groups. It is calculated starting from a variance analysis (ANOVA) performed on the data matrix composed of the participants on the rows and the results of the tests on the columns. If the data row of the matrix is composed of less than two valid data, it is automatically deleted before calculating the ICC. If the row consists of two valid data, then the third value will be the average between the two. If all three data are valid, the row does not change before the ICC is calculated.

The ICC ranges from 0 to 1.

ICC	Meaning
1 – 0.75	High similarity between values of the same group
0.75–0.4	There is similarity between values of the same group
0.4 – 0.0	Values from the same group are not similar
< 0	Typically, this happens when the between-subject variation is relatively small compared to the within-subject variation. If that is the case the negative ICC estimate produced by the software should not be quoted but we can say that the scale is not reliable. [https://www.kcl.ac.uk/ioppn/depts/BiostatisticsHealthInformatics/SAS/faqs9]

In the end, thanks to the 'xlswrite' function the data are tabulated and divided according to the task and features they correspond to. Final results are reported in the next chapter.

7 RESULTS

In this chapter we present the obtained results: first analysing case by case and then comparing all the data.

7.1 EXTRACTED FEATURES

The algorithm has extracted the following parameters from the data:

1. APA duration (from the onset to the end of APAs). This implies the definition of:
   a. APA onset

      The onset of APAs (first measurable change in CoP from baseline) was detected by an automated threshold-based algorithm, with threshold set as twice the SD of signal during the initial, pre-step initiation, period of each trial. The algorithm was used to determine the onset of both ML and AP CoP and to set the first one (in terms of time) as the 'APA onset'.

   b. APA end

      The APA was considered completed when the toe is raised (toe off).
2. APA ML amplitude, that is
   a. Peak ML-CoP, peak lateral CoP excursion toward the swing foot from baseline and
   b. Peak ML-Acc, peak acceleration toward the stance foot of the lateral trunk acceleration;
3. APA AP amplitude, that is
   a. Peak AP-CoP, peak of backward CoP excursion and
   b. Peak AP-Acc, forward trunk acceleration from the baseline.
4. Relative time-to-peak, from the onset of APAs to the instant of each peak APA, was also measured.
   a. Time to peak ML, the time period between the APA onset and the CoP ML peak
   b. Time to peak AP, the time period between the APA onset and the CoP AP peak

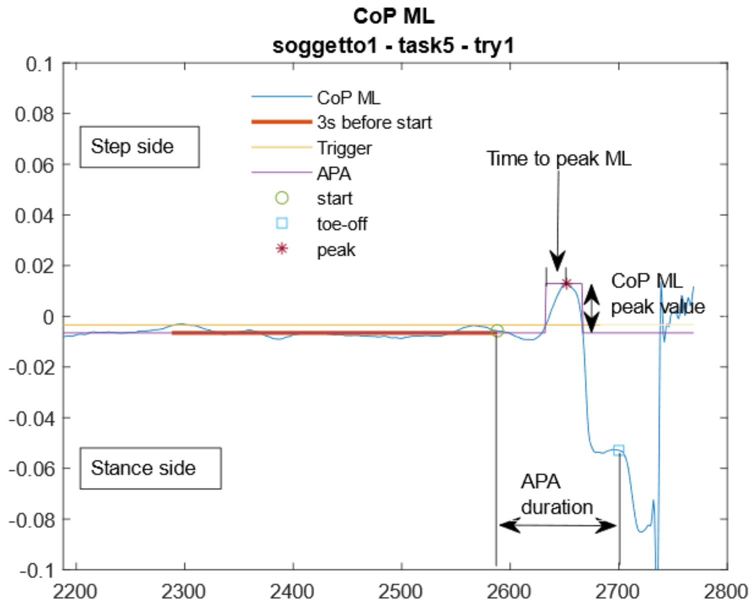


Figure 22: extrated features

7.2 Results of individual tasks - Analysis and comparison with the literature

The algorithms, which were explained in the previous chapter, allowed us to obtain useful data for all the variables except for the anterior posterior trunk acceleration (Acc AP). The data obtained were not enough for a statistical estimate. In most cases the anteroposterior acceleration peak of the trunk did not exceed the threshold value.

Tasks 6 and 14 do not provide useful data for their analysis, for this reason they have been excluded.

7.2.1.1 Task 6 – 1 step backward

As far as task 6 is concerned, it was not suitable for the algorithm because:

- The CoP ML signal in most cases does not present peaks before the toe off but a monotonic growth. It is evident that this growth is because the weight moves on the stance leg to make a step in the lateral direction.

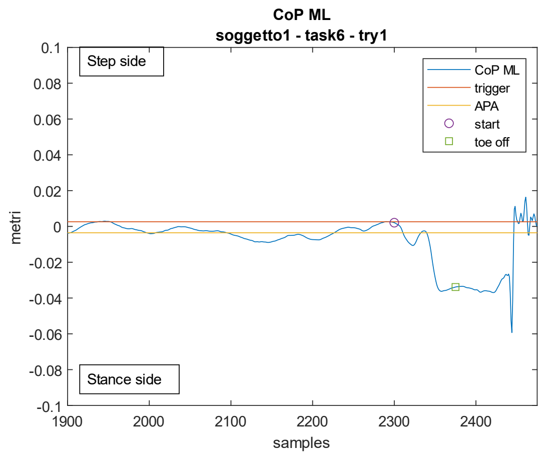


Figure 23

- The acceleration of the mediolateral trunk has peaks higher than the trigger. In this study the task 6 was not considered suitable since the algorithm is not able to detect the parameters for the other signals and therefore compare them.

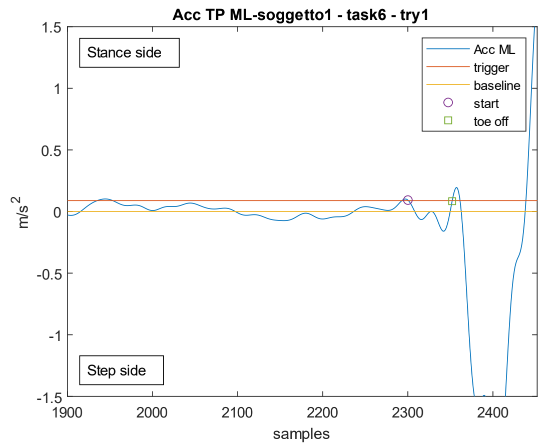


Figure 24

- The CoP AP has no noticeable peaks. Regarding the acceleration of the trunk (Acc AP), the observations are the same. This is explained by the fact that the subject does not have to make movements in the longitudinal plane so does not need preparatory movements on it.

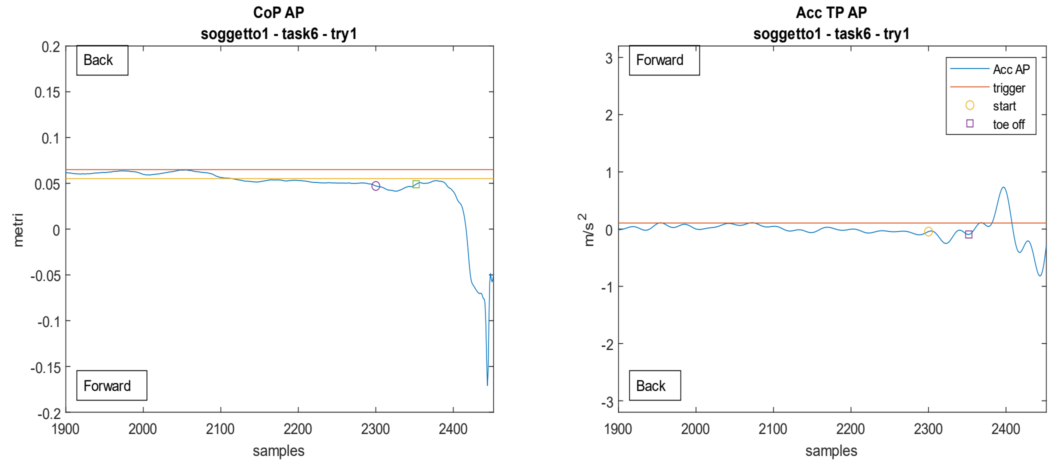


Figure 25

7.2.1.2 Task 14 - rise on toes. Take 1 step

Task 14 has been excluded from the overall analysis since, in most cases, during the three seconds preceding the start, the signal has a standard deviation higher than the maximum one. This is true both in the mediolateral and anteroposterior direction.

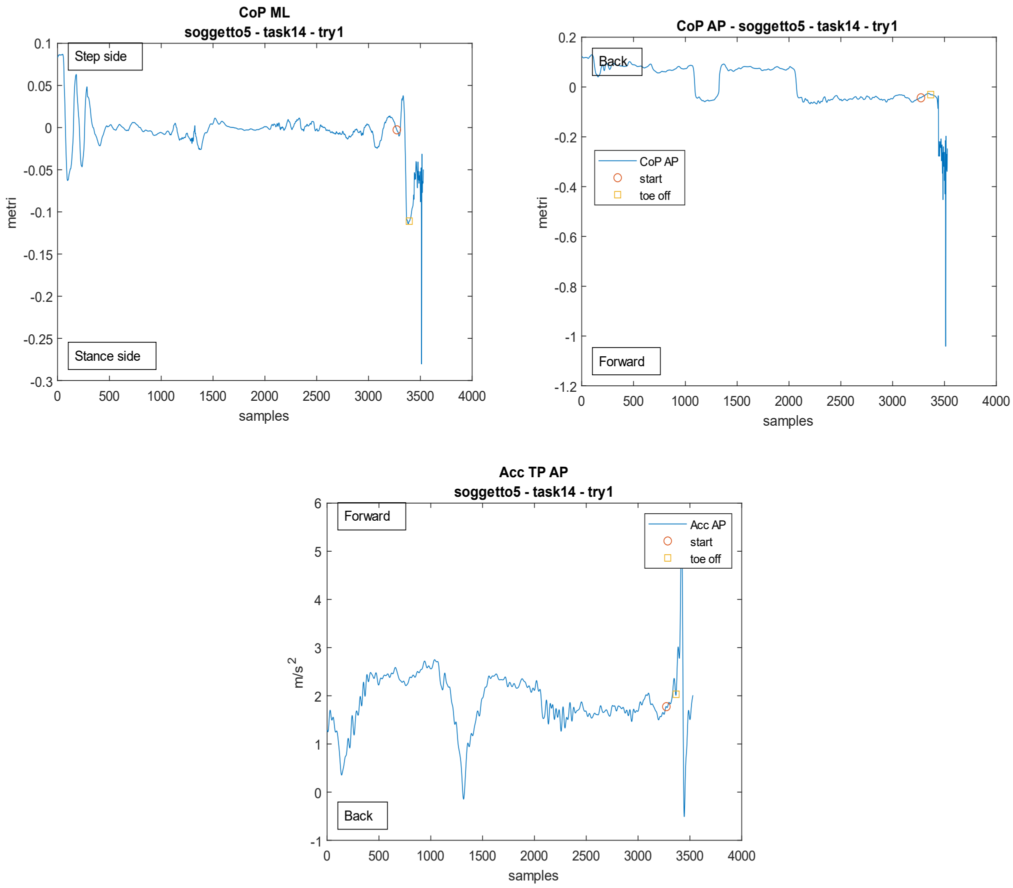
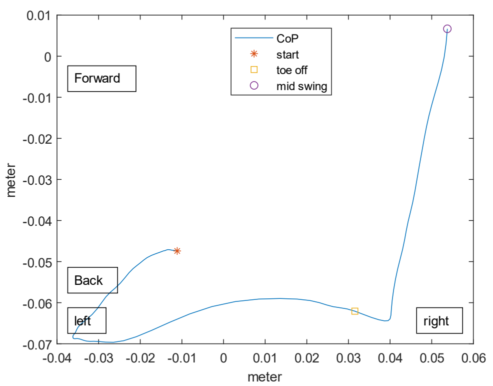


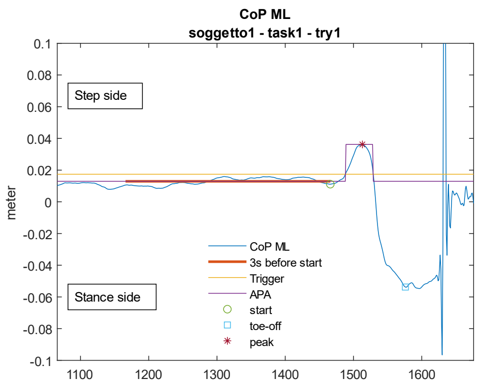
Figure 26

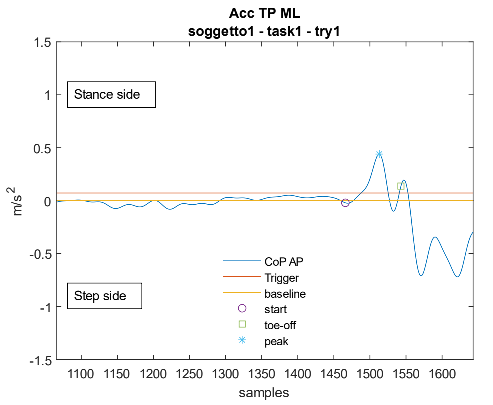
This is due to the fact that the required position (rise on toes) does not allow a sufficiently large support base to allow the subject to stabilize his centre of pressure and the acceleration of the trunk.

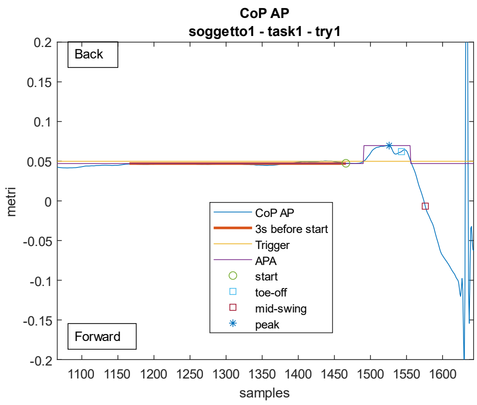
7.2.1.3 Task 1 – 1 step forward

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,66	0,34	2,94	70,00	33,15	48,15
SD	0,96	0,07	2,13	27,75	15,67	18,51
ICC	0,96	0,85	0,96	0,66	0,23	0,25







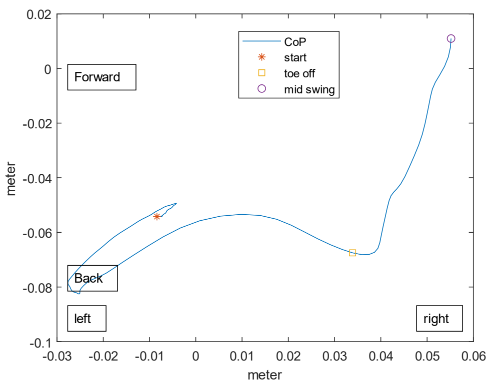


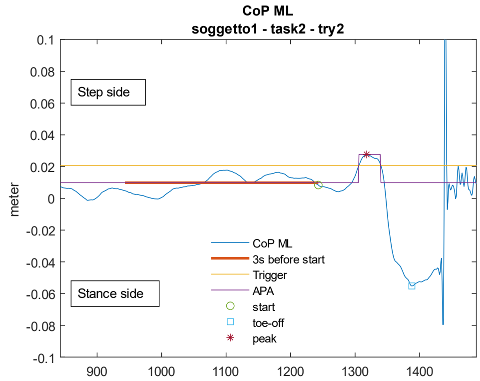
The graphs shown above are of a subject with left dominant leg. This can be clearly seen from the CoP progress starting from the start signal to the mid swing. The subject moves his weight initially on the left leg so that the dominant leg can then push the body forward, shifting the weight to the right. It's noticeable that the AP CoP does not come back to the baseline before the toe off. This means that the heel is detached from the ground even before the trunk has returned to its starting position. This phenomenon has been observed in most cases but not in all. Subjects in which this event does not appear do not have particularly different parameters. In the future analysis can be made in this sense, in this study the studied population is too limited to determine which of the two signals is the norm. This phenomenon resulted verified in many studies like Rocchi et al.[14]

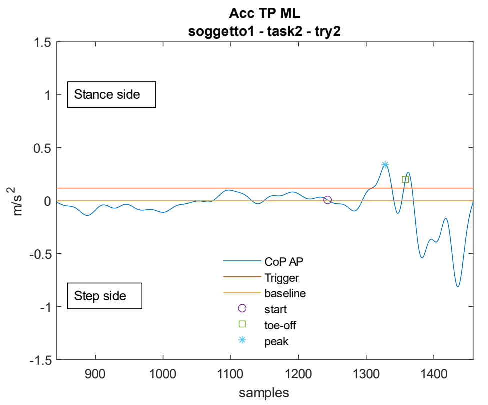
Regarding to the CoP AP data, those obtained are higher than those by Rocchi L. et al.[14]. At the same time though, the data obtained by Mancini M.[15] et al. appear to be very similar to those obtained in this test. In the study by Mancini M.[15] et al. the data turns out to be about 1 cm more than the actual results. Furthermore, the data of the mediolateral peak of the CoP are 1-2 cm lower than the studies previously mentioned as well as the average value of the Acc ML peak which is 0.01g lower. It is important to say that the cited studies required the subject to take two steps and not 1.

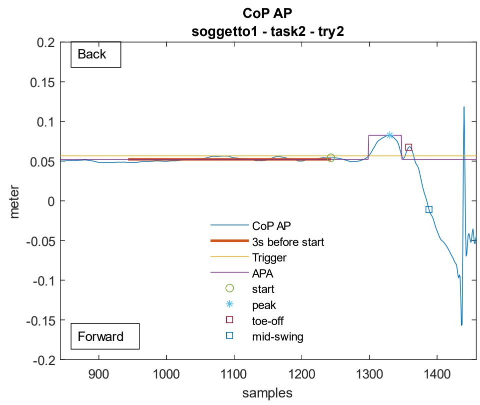
7.2.1.4 Task 2 – 3 steps forward

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,98	0,46	4,01	68,29	31,93	55,14
SD	1,23	0,12	1,73	21,81	12,58	13,61
ICC	0,57	0,74	0,54	0,44	0,01	0,01





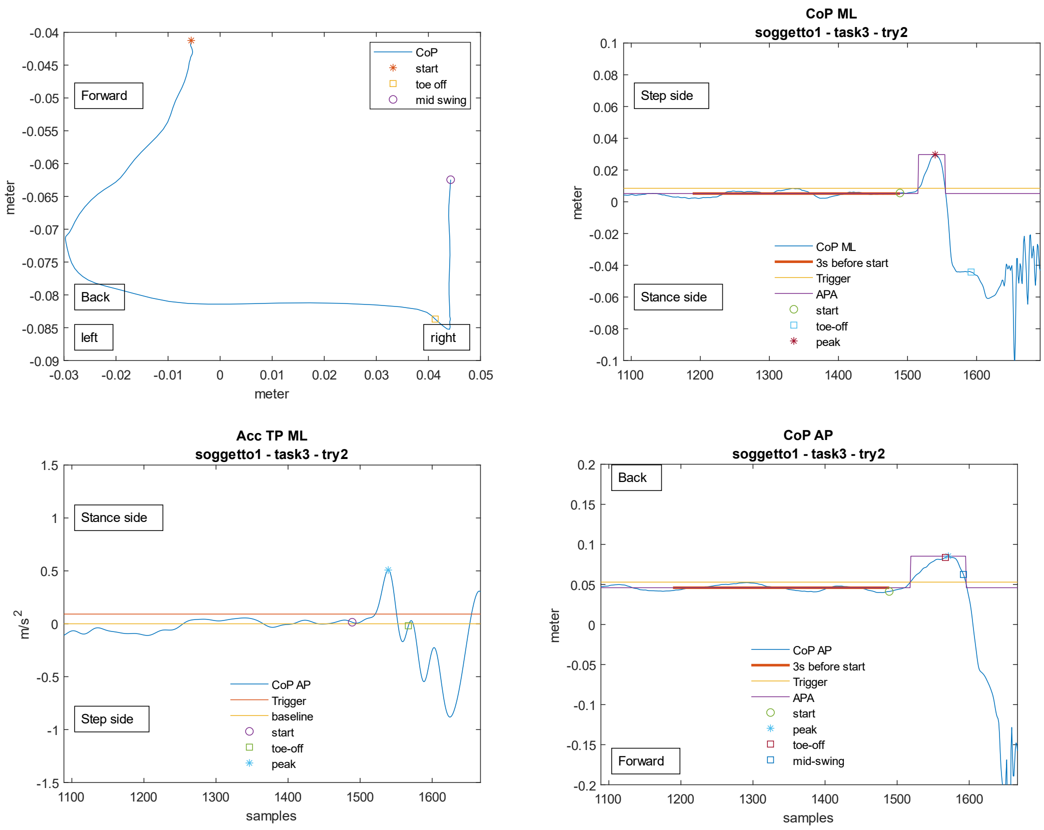




In a morphological point of view the graphs shown are similar to those shown in task 1.

7.2.1.5 Task 3 – start walking

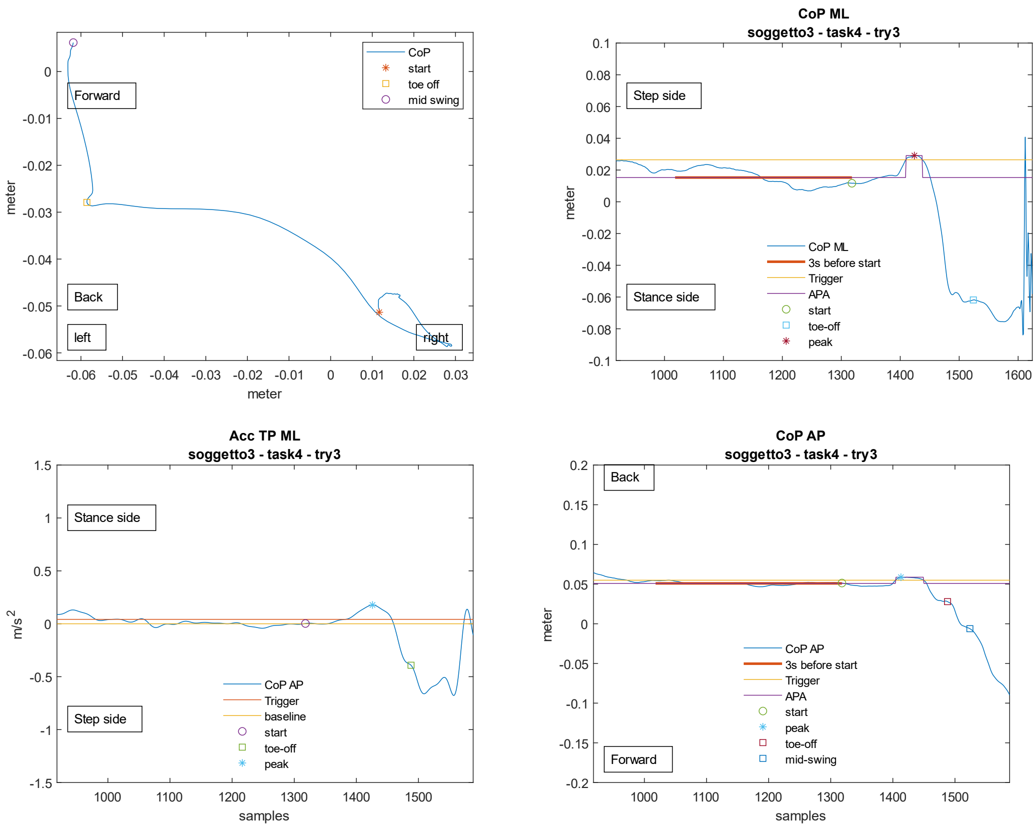
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	3,08	0,45	4,12	55,08	23,00	45,54
SD	0,84	0,11	1,30	8,24	3,95	10,63
ICC	0,43	0,48	0,62	0,35	0,02	0,23



The values are similar to task 1. For a comparison see the discussion. The data are on average lower both in the acceleration peak and in the CoP when compared with the results obtained on healthy subjects in the study by Mancini M. et al.[27]. Time to peak AP and ML have high intra class variability.

7.2.1.6 Task 4 – 1 step slowly

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,60	0,35	2,00	75,50	22,60	43,70
SD	1,45	0,23	0,92	28,87	4,02	20,91
ICC	0,62	0,93	0,52	0,87	0,01	0,82



The subject 3 in the graph has right dominant leg.

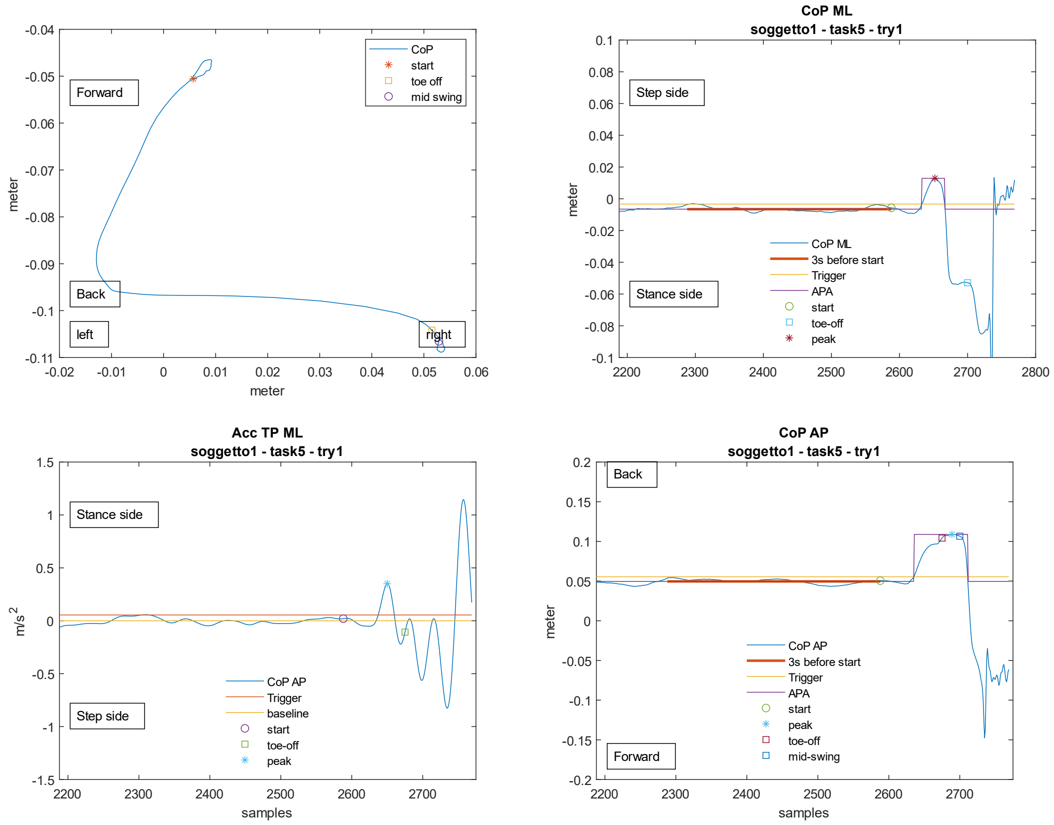
In this task it was required to take a step forward slowly. The CoP AP peak always returns to the baseline value before the toe off. This can also be guessed from the high time difference between time to peak AP and the duration of the APA.

The speed of the movement has affected the peak values of the cop that are lower than those of a normal step forward. For a comparison analysis see the discussion.

No data reported from the literature.

7.2.1.7 Task 5 – 1 step fast

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,54	0,35	7,47	48,45	22,27	59,18
SD	1,13	0,07	1,83	19,45	7,95	24,16
ICC	0,73	-0,47	0,92	-0,42	-0,03	0,59

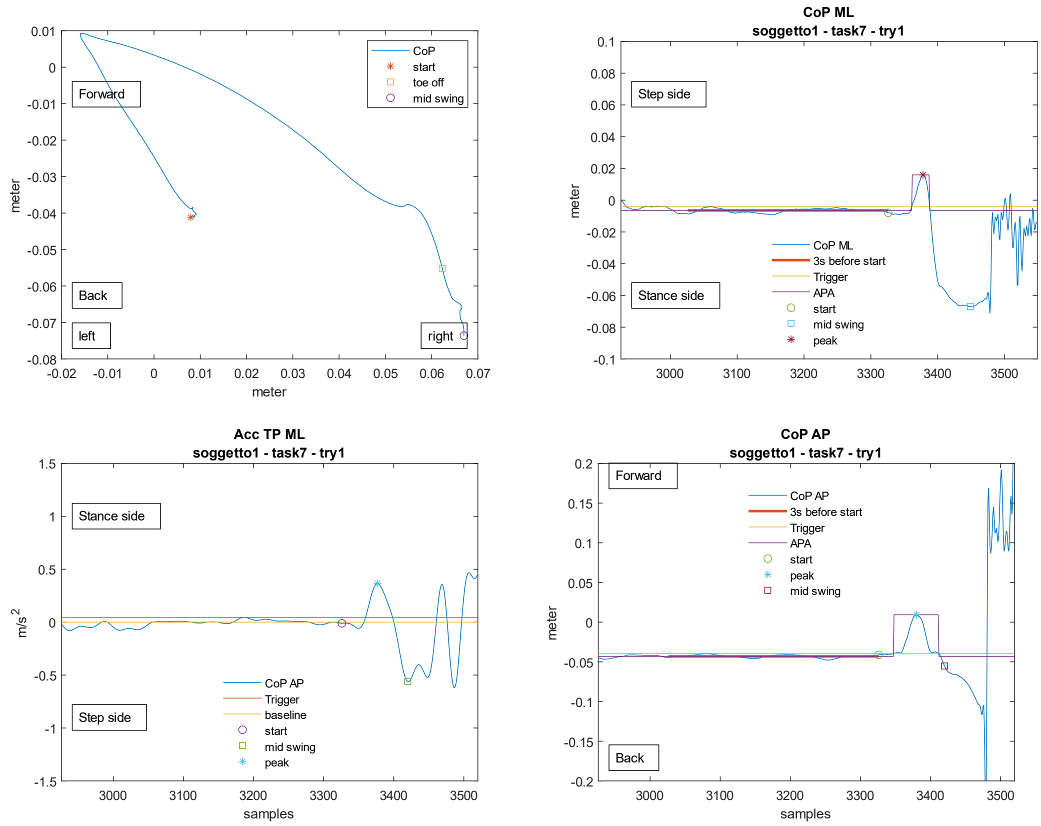


This task required a rapid step forward. The effect of this request can be seen on the arrangement of the cop. The toe off and mid swing are extremely close in terms of time. Also, during the transition from step leg to stance leg, the centre of pressure shows no sign of returning to its baseline value. In fact, this affects the position of the AP peak that appears to be after the toe off.

Regarding to the values of CoP AP peak obtained here are larger (about 1 cm more) than those obtained by Rocchi et al.[14].

7.2.1.8 *Task 7 – 1 step backward*

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,91	0,53	-4,96	80,42	28,75	43,08
SD	1,14	0,29	2,73	13,27	8,55	32,50
ICC	0,74	0,85	0,84	0,63	-0,32	0,72

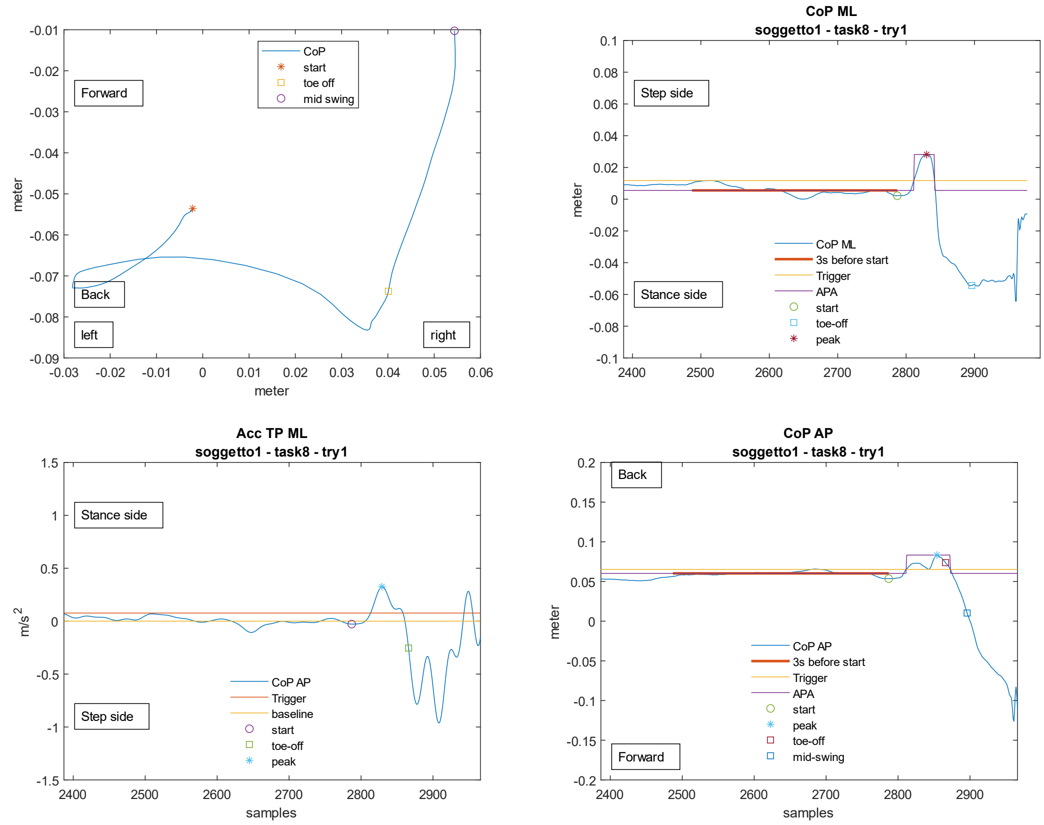


Task 7 consists of a backward step. This change of direction basically influences the anterior posterior development of the cop. The centre of pressure moves forward with an amplitude comparable to that of a step forward. The general trend of the other parameters is like a normal step.

This behaviour makes sense because the anticipatory movements must oppose the future movement to allow it to be balanced. In fact, the only thing that changes after a normal step is the direction on the anteroposterior plane.

7.2.1.9 Task 8 – 1 step with 23cm obstacle

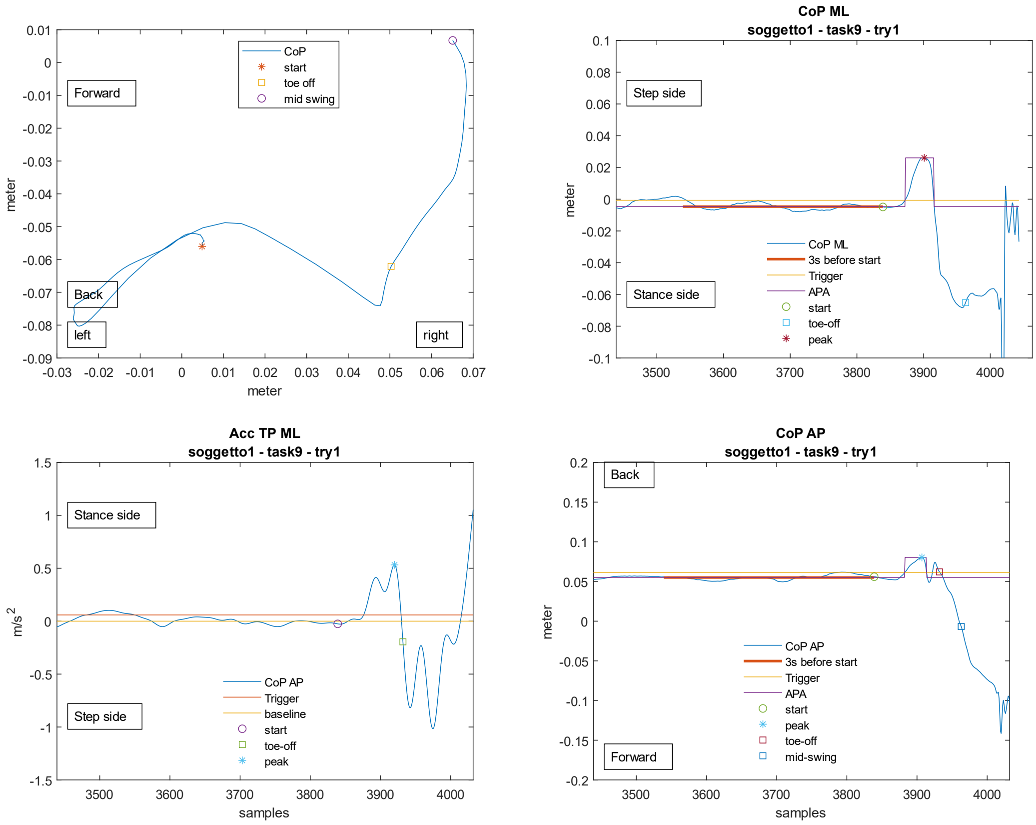
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [sec]	Time to peak ML [sec]	Time to peak AP [sec]
AVE	3,51	0,52	3,25	71,93	29,57	42,64
SD	1,09	0,13	2,24	24,77	10,17	13,37
ICC	0,45	0,20	0,88	0,69	0,08	0,32



See the discussion for the comparison.

7.2.1.10 Task 9 – 1 step with 30cm obstacle

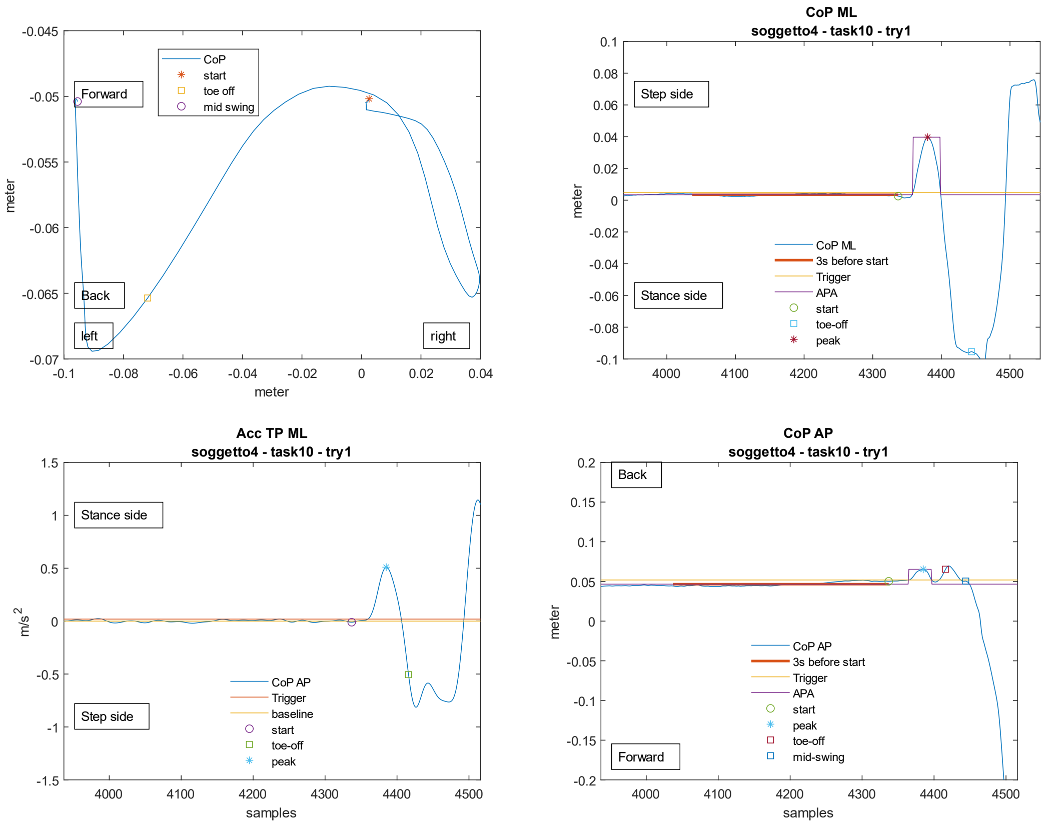
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [sec]	Time to peak ML [sec]	Time to peak AP [sec]
AVE	3,97	0,60	3,10	67,15	31,54	47,23
SD	1,53	0,26	1,29	16,11	8,24	9,71
ICC	0,87	0,84	0,54	0,87	0,56	-0,14



The CoP signal undergoes a strong forward deviation and then turns back before raising the foot. This may be because the subject is forced to raise his leg more than normal and therefore a further compensatory movement is necessary. This is visible in the anteroposterior direction as two consecutive waves before the toe off.

7.2.1.11 Task 10 – 1 short step

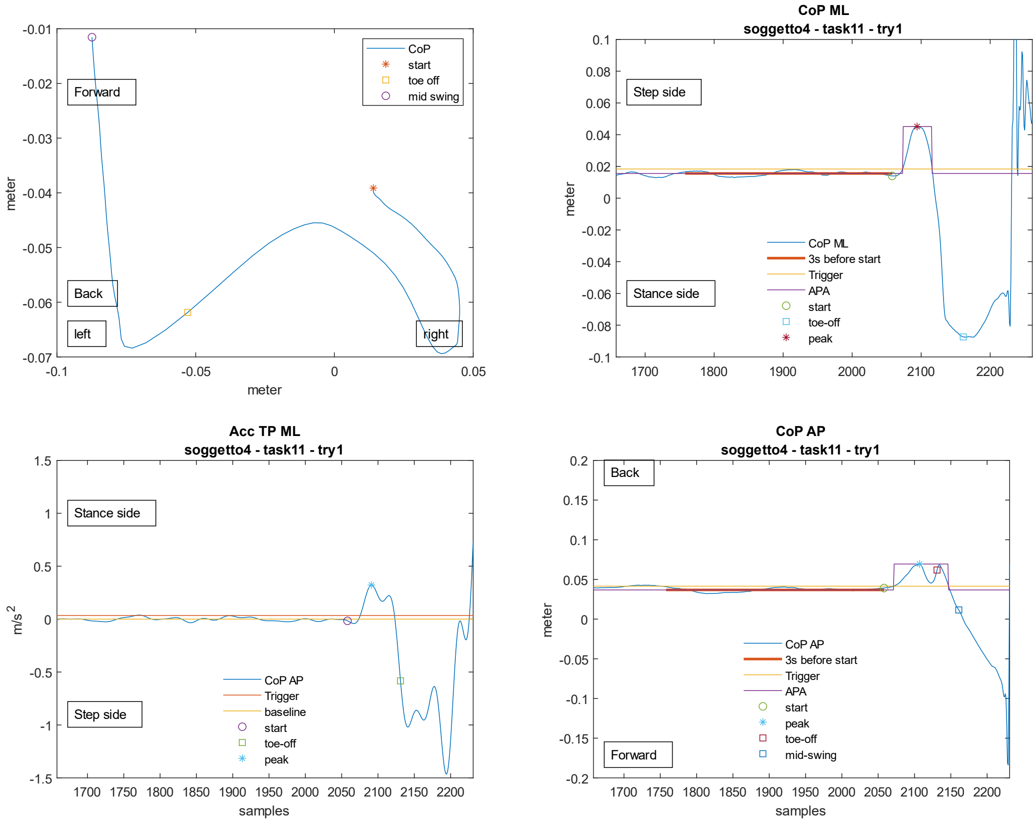
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,08	0,32	2,82	59,36	25,91	48,91
SD	0,82	0,07	1,83	26,01	12,65	13,07
ICC	0,52	0,56	0,87	0,92	0,45	0,34



Task 10 consists of a short step in the forward direction. The data obtained for the CoP AP are consistent with those presented in the paper by Rocchi L. et al .[14]

7.2.1.12 Task 11 – 1 long step

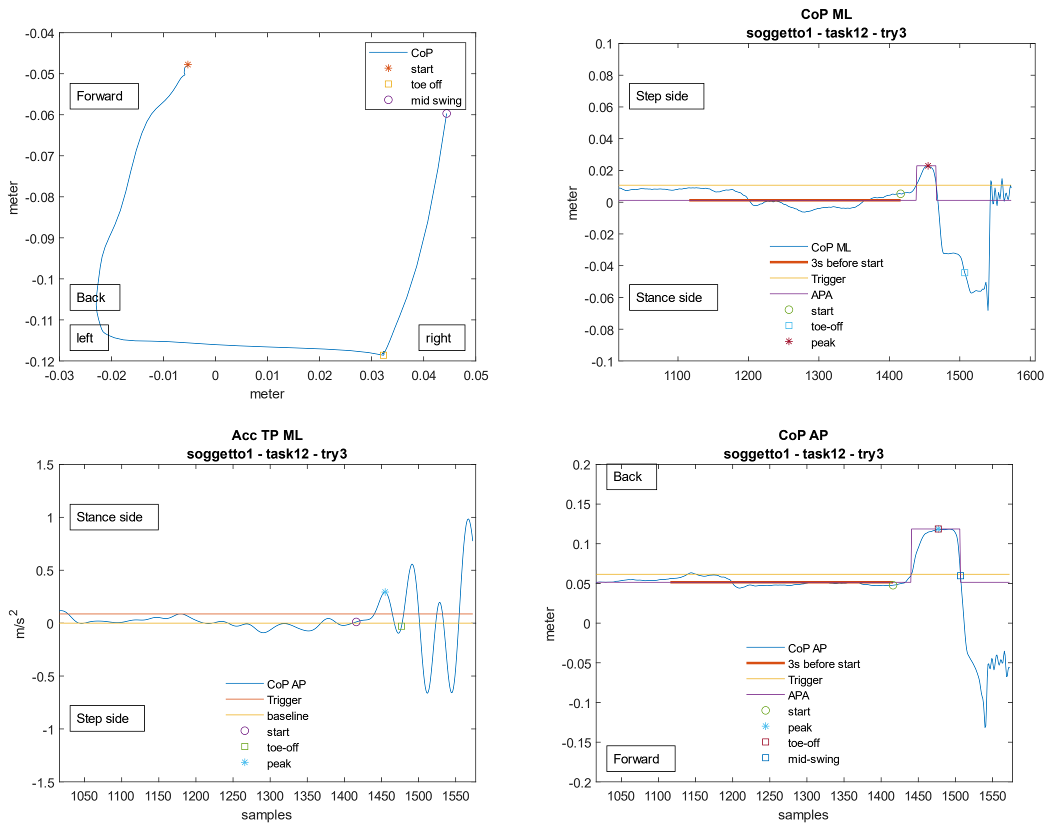
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	2,99	0,39	3,65	62,13	25,60	49,20
SD	1,53	0,09	1,97	22,73	9,27	9,23
ICC	0,75	0,23	0,87	0,82	0,08	-0,16



The data obtained for the CoP AP are consistent with those presented in the paper by Rocchi L. et al .[13]

7.2.1.13 Task 12 – 1 step. Start as soon as possible

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	4,16	0,53	6,48	40,54	20,00	38,23
SD	1,18	0,25	0,90	3,97	2,97	6,20
ICC	0,47	0,67	0,38	-0,07	-0,18	-0,04

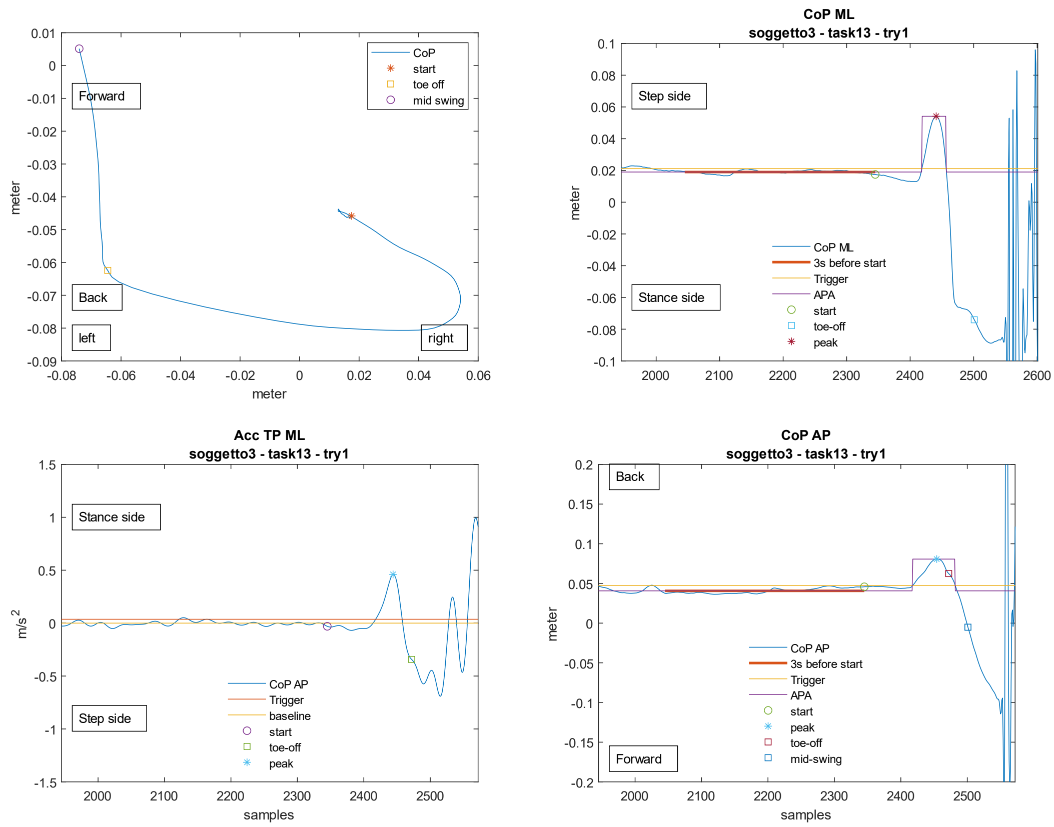


In this task the variation of the anticipatory movements to the path is evaluated when a rapid reaction is requested. It is noticeable that the foot is raised after the lateral movement of the CoP. During the lateral transition there is no deflections and the AP peak coincide with the toe off.

As soon as the step was over, the subjects tended to oscillate or lose balance slightly. It can be concluded that a rapid reaction leads to anticipatory movements that are not optimal for maintaining balance.

7.2.1.14 Task 13 – 1 step, eyes closed

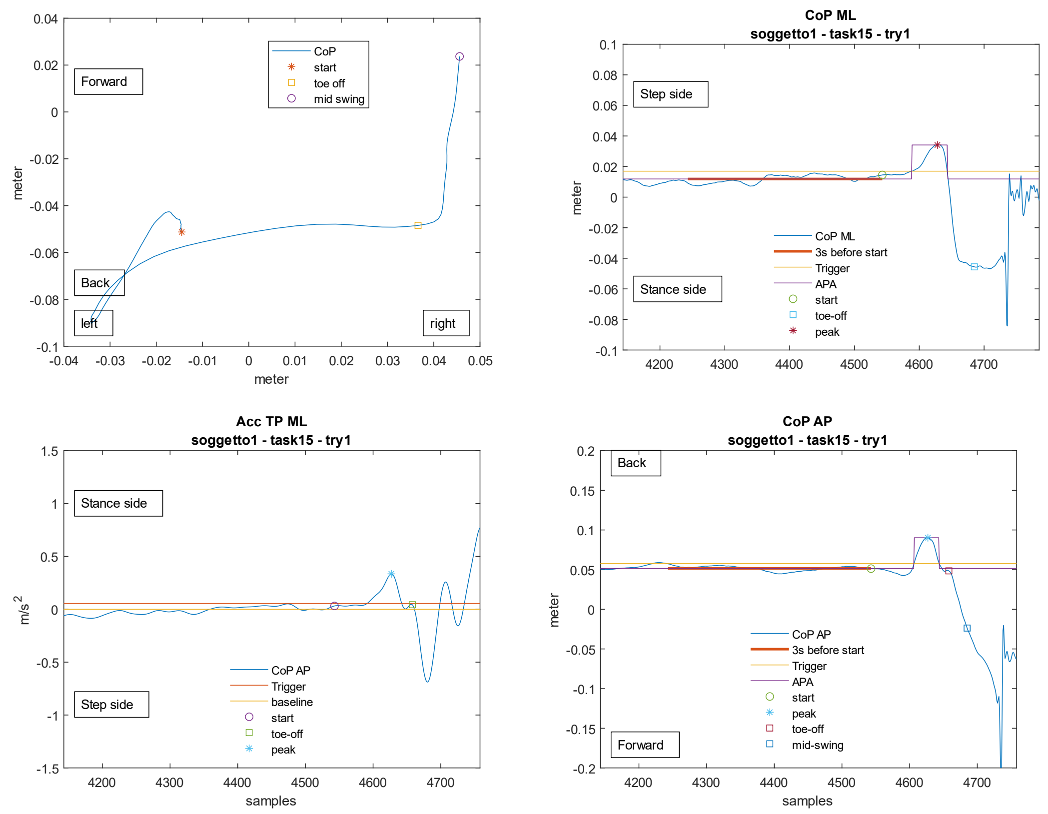
	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	3,23	0,48	3,83	59,07	22,67	38,73
SD	1,09	0,08	1,16	10,84	4,88	6,34
ICC	0,61	0,69	0,51	0,72	0,25	-0,26



See discussion for comparison.

7.2.1.15 Task 15 – 1 step with a cognitive task

	CoP ML peak value [cm]	Acc ML peak value [m/s^2]	CoP AP peak value [cm]	Duration [csec]	Time to peak ML [csec]	Time to peak AP [csec]
AVE	3,55	0,57	4,63	57,25	29,75	52,25
SD	1,07	0,23	0,57	6,94	7,77	13,18
ICC	0,78	0,70	0,46	0,78	0,14	0,24



It is worth noting that the subjects just before and during the execution of the step stopped the cognitive task or made mistakes. Despite the presence of the cognitive task the general curve of the values remains unchanged. For an evaluation and comparison of the measured parameters see the discussion.

7.3 Overall results

The graphs in which the results of the different tasks are compared with each other are showed below.

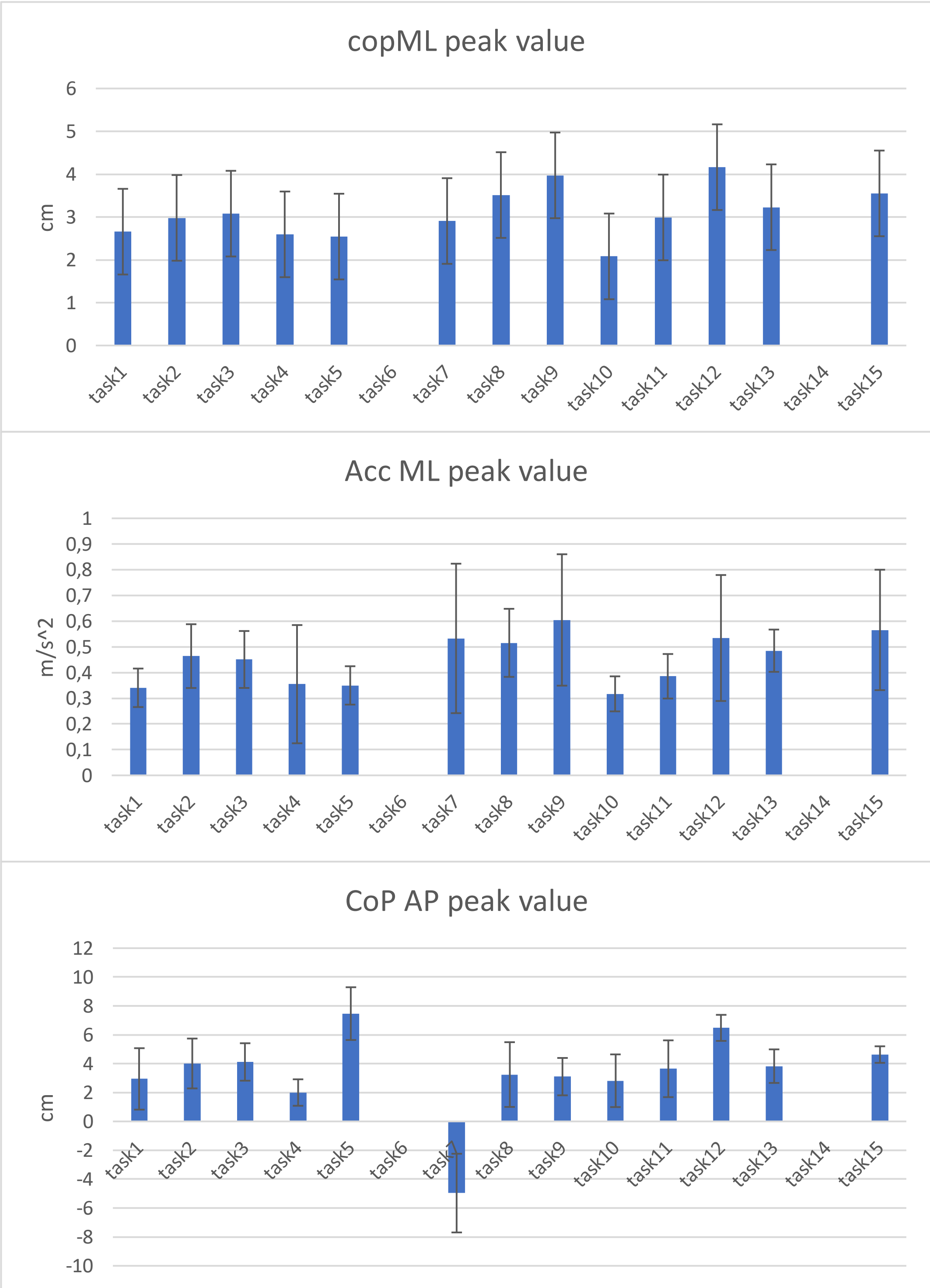
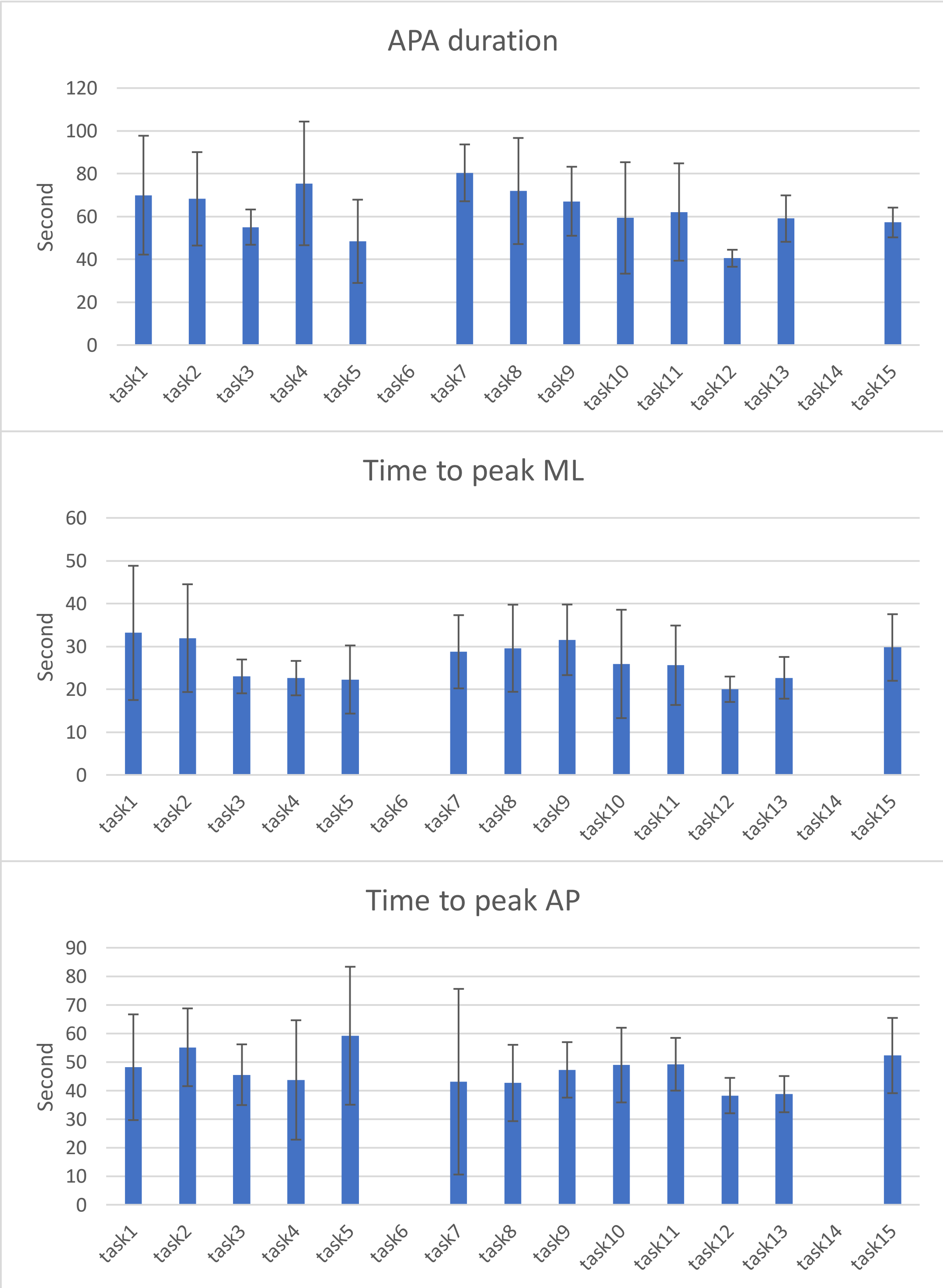


Figure 27



APA duration
Second
120
100
80
60
40
20
0
task1
task2
task3
task4
task5
task6
task7
task8
task9
task10
task11
task12
task13
task14
task15
Time to peak ML
Second
60
50
40
30
20
10
0
task1
task2
task3
task4
task5
task6
task7
task8
task9
task10
task11
task12
task13
task14
task15
Time to peak AP
Second
90
80
70
60
50
40
30
20
10
0
task1
task2
task3
task4
task5
task6
task7
task8
task9
task10
task11
task12
task13
task14
task15

Figure 28

8 DISCUSSION AND DATA ANALYSIS

In this chapter we will analyse the tasks and their signals not individually but in groups. We will see how a certain variable influences the properties of the APAs. The author also reports an overall analysis: which variables are more relevant and an ICC analysis.

8.1 HOW THE VARIABLES AFFECT THE SIGNALS

The variables analysed are:

1. Number of steps
2. The speed of the step
3. The presence of obstacle at different height
4. The length of the step
5. The reaction time
6. The sight (eyes close or not)
7. The presence of a cognitive task

8.1.1 Varying the number of steps

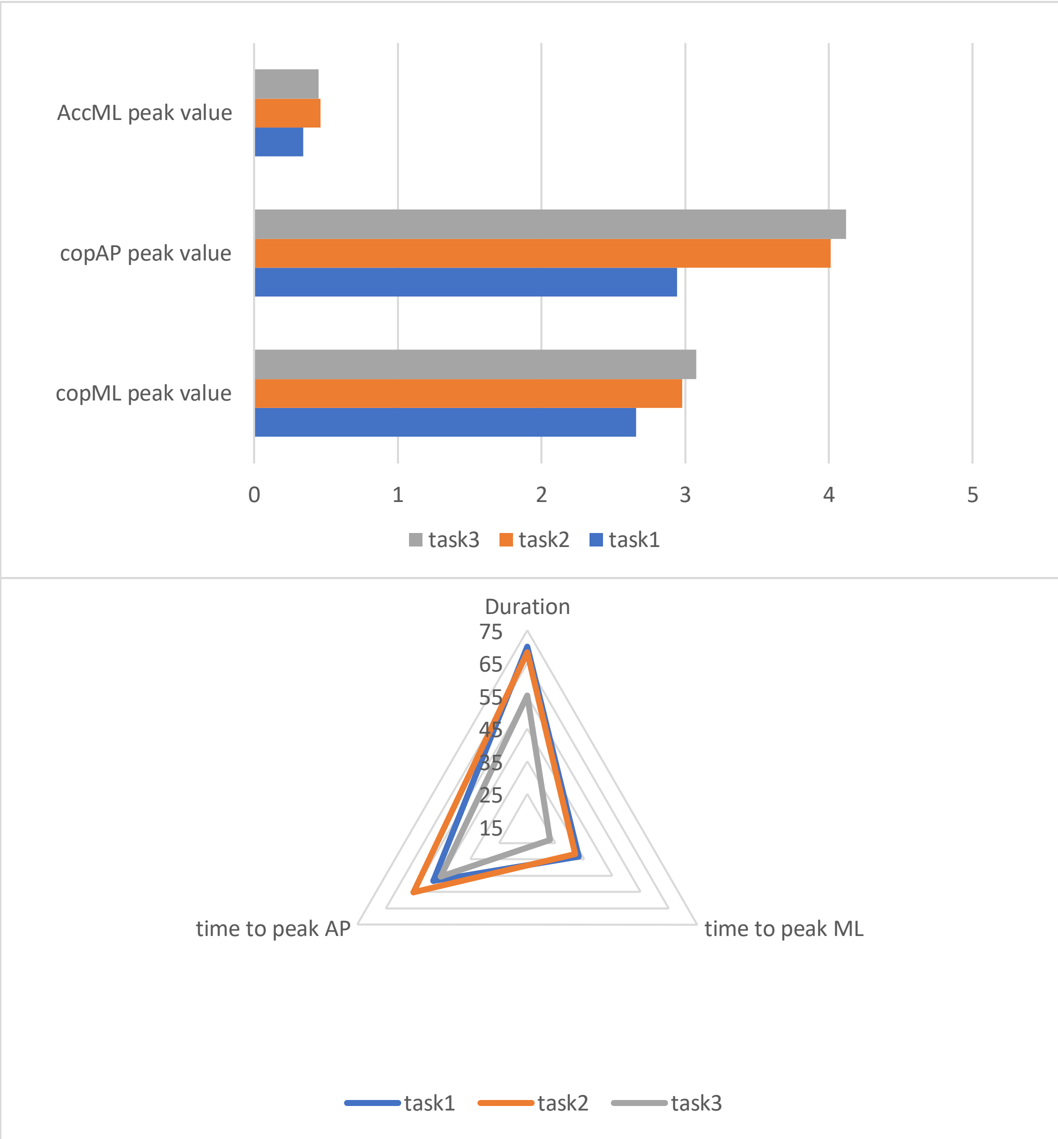


Figure 29

From the extracted data we can see that the more the number of steps, the larger the values of the CoP AP and ML peaks.

Regarding the time to peak ML and the duration, task 1 and task 2 are almost equivalent but the gait initiation (task 3) presents minor values.

In conclusion, **initiating a step requires a longer APA with minor CoP peak than initiating gait**.

8.1.2 Varying the speed of the step

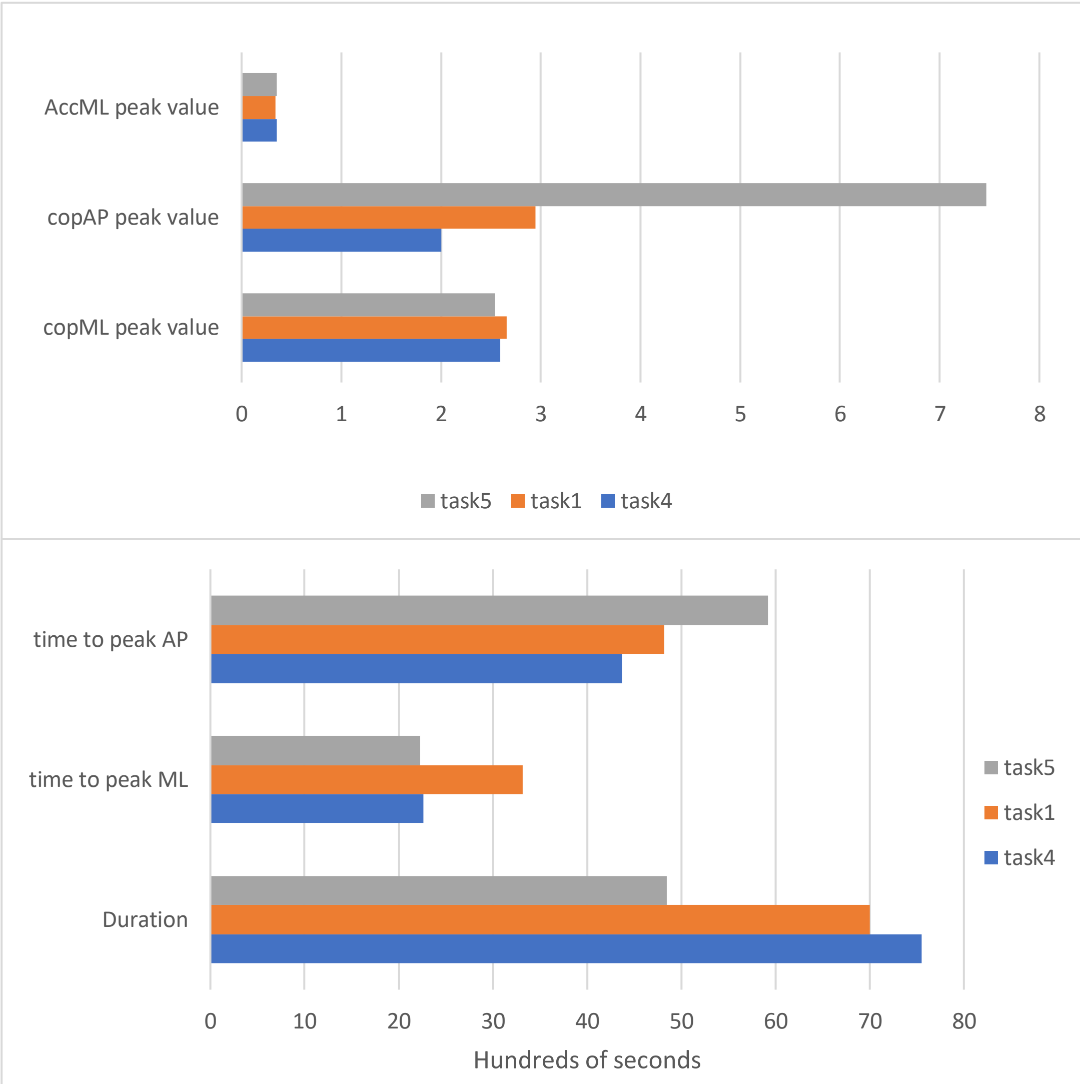


Figure 30

Increasing the step speed, we can observe a strong growth in the anteroposterior peak of the CoP and the time to peak AP. Moreover, the slower the step the longer the APA duration.

On average the CoP ML peak value does not show noticeable variations.

8.1.3 Varying the height of the obstacle

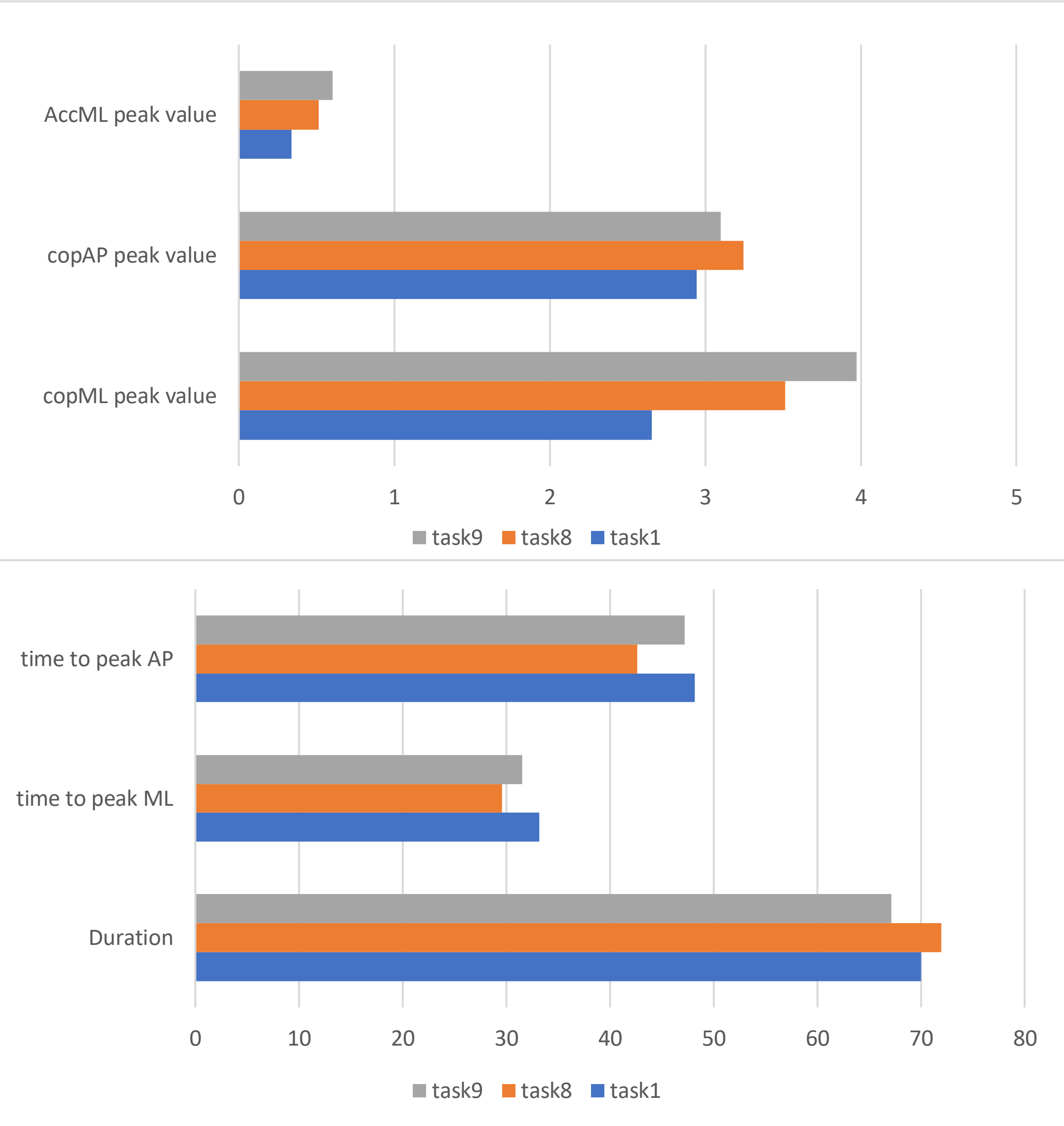


Figure 31

The only trend that the data obtained show is the increase in the amplitude of the mid-lateral peak as the height of the obstacle increases.

8.1.4 Varying the length of the step

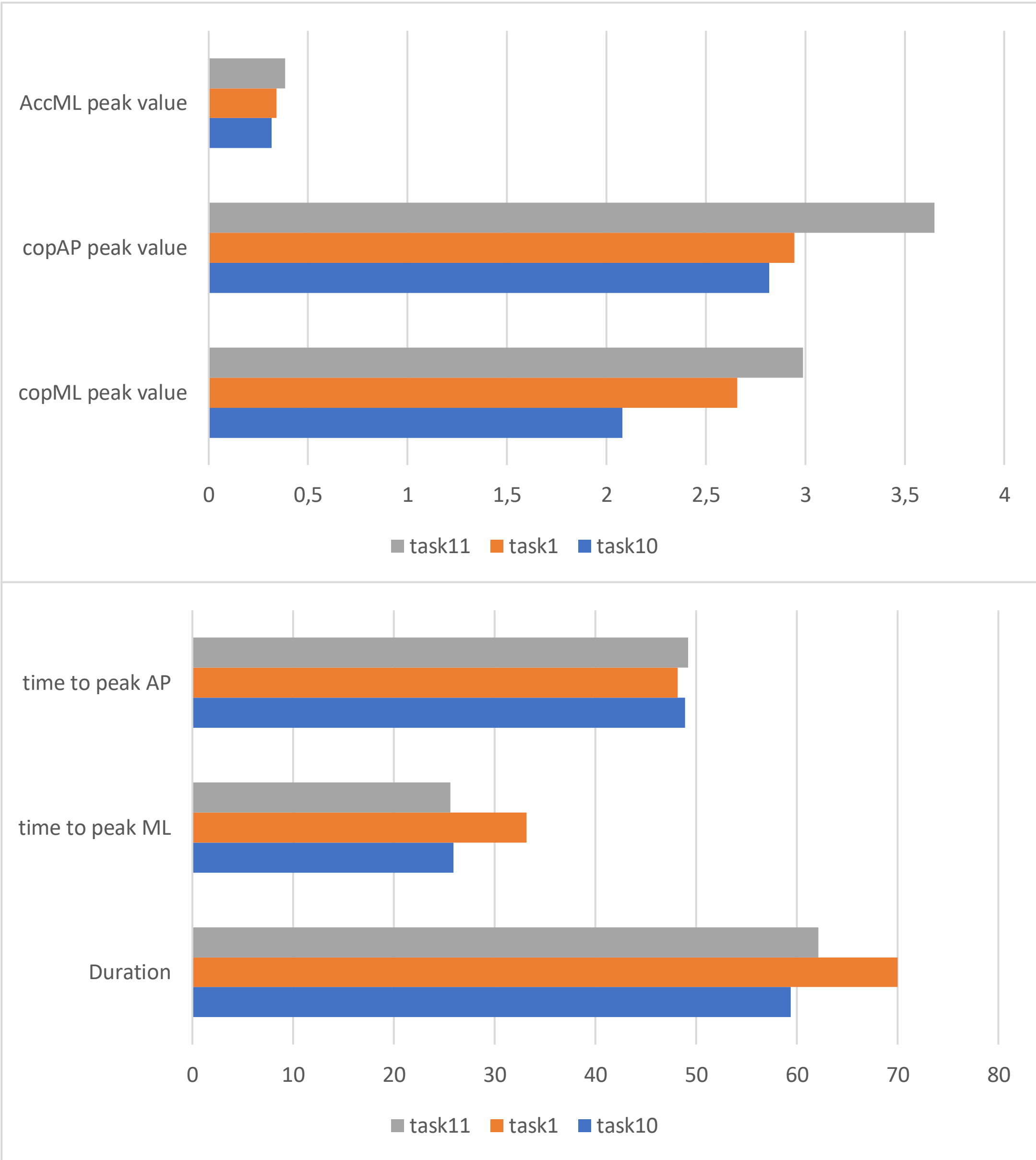


Figure 32

We can see an increase in the AP and ML peak as the step length increases. It is interesting to note that a step of normal length requires on average an APA longer than a long or short step.

8.1.5 Varying the reaction time

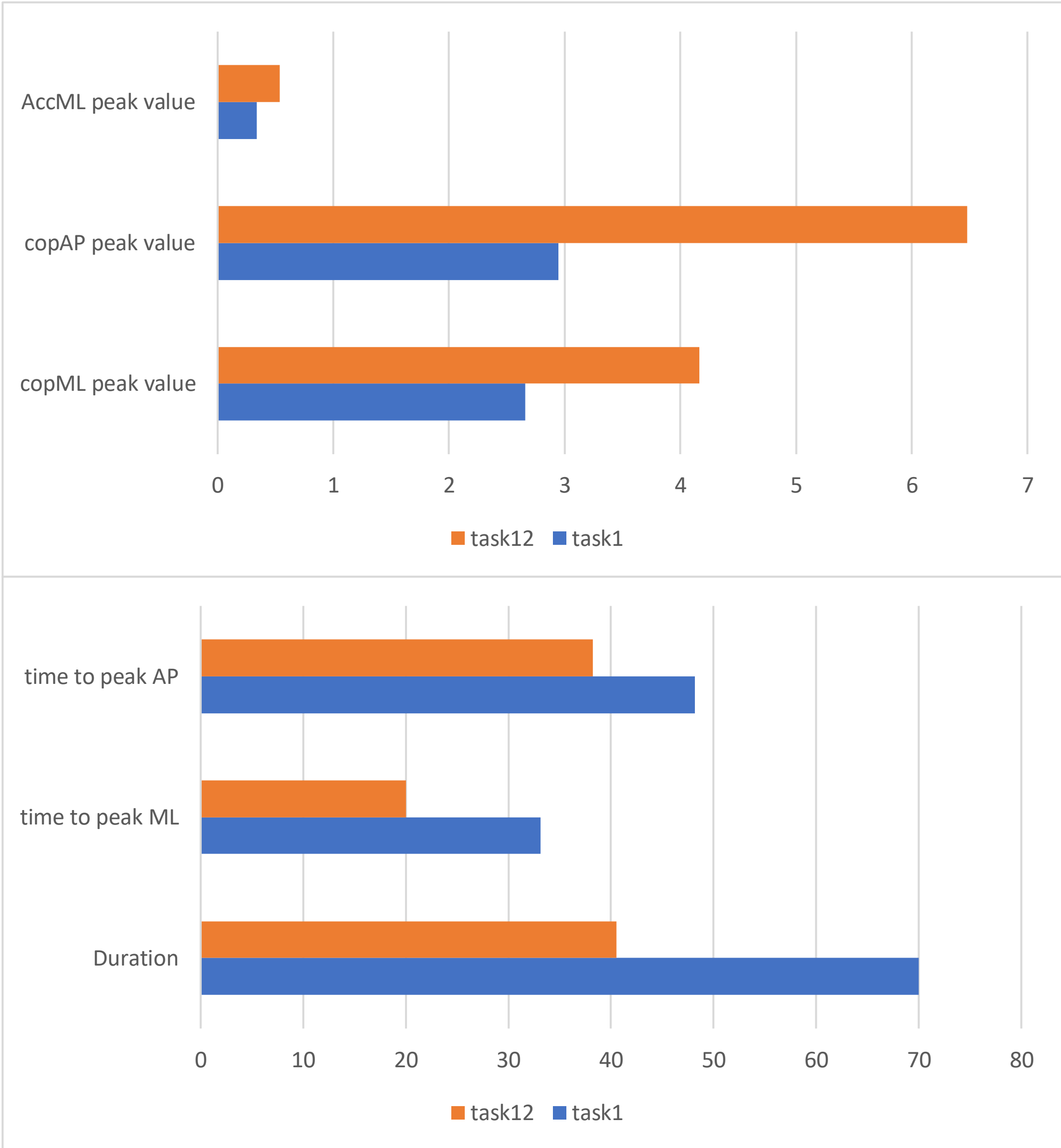


Figure 33

This task, by its very definition, leads to a reduction in the preparation time and in how long the APA takes to reach its peaks. At the same time, both the ML and AP peaks are of greater amplitude than a task with a self-chosen reaction time.

8.1.6 With eyes closed

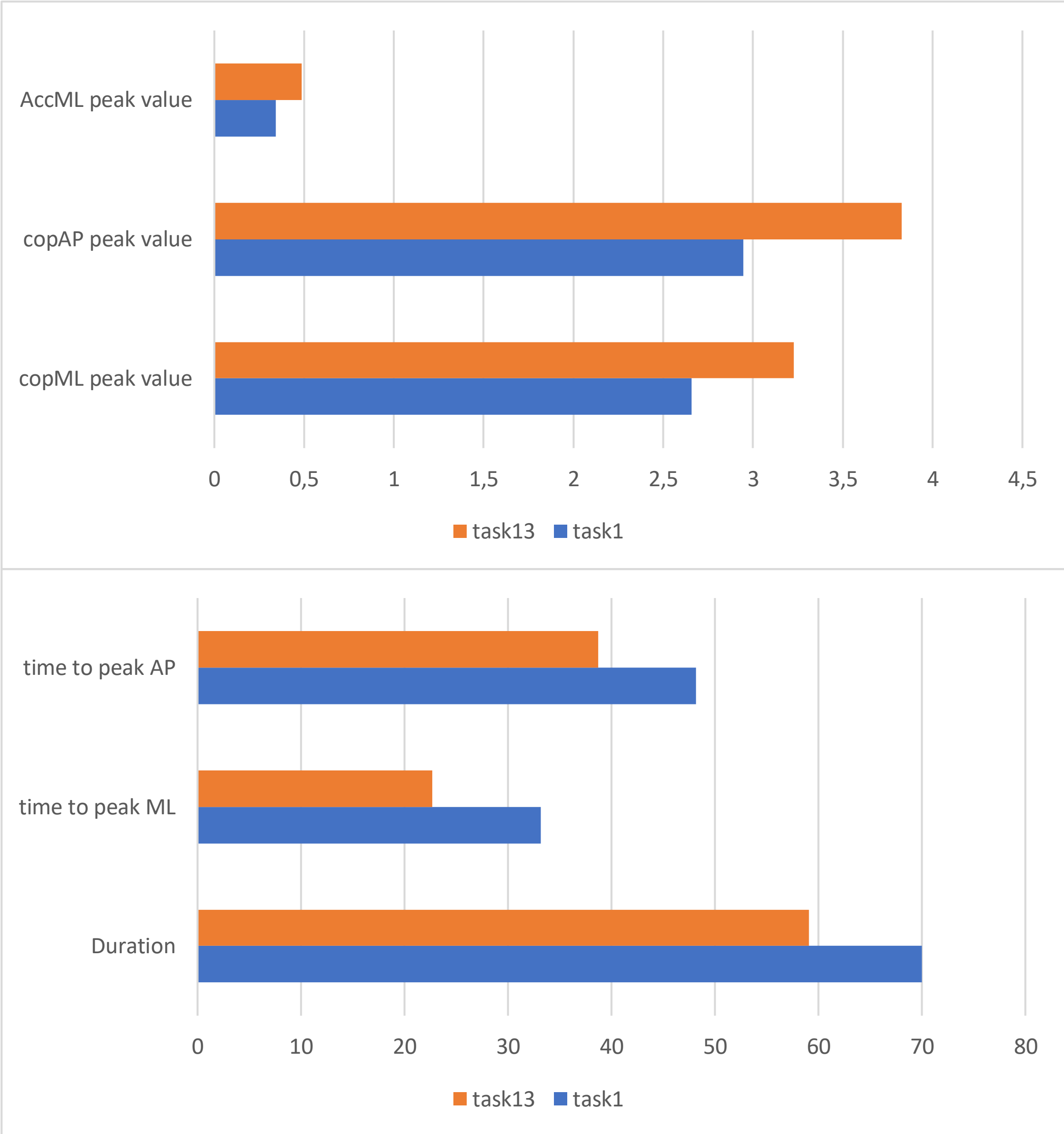


Figure 34

In the subjects studied, the average APA duration for a step with closed eyes is shorter than a normal step. ML and AP time to peak are also lower than task 1. The peaks are higher than a normal step.

Overall, there is a decline in terms of duration and an increase in terms of peak value.

8.1.7 With a cognitive task

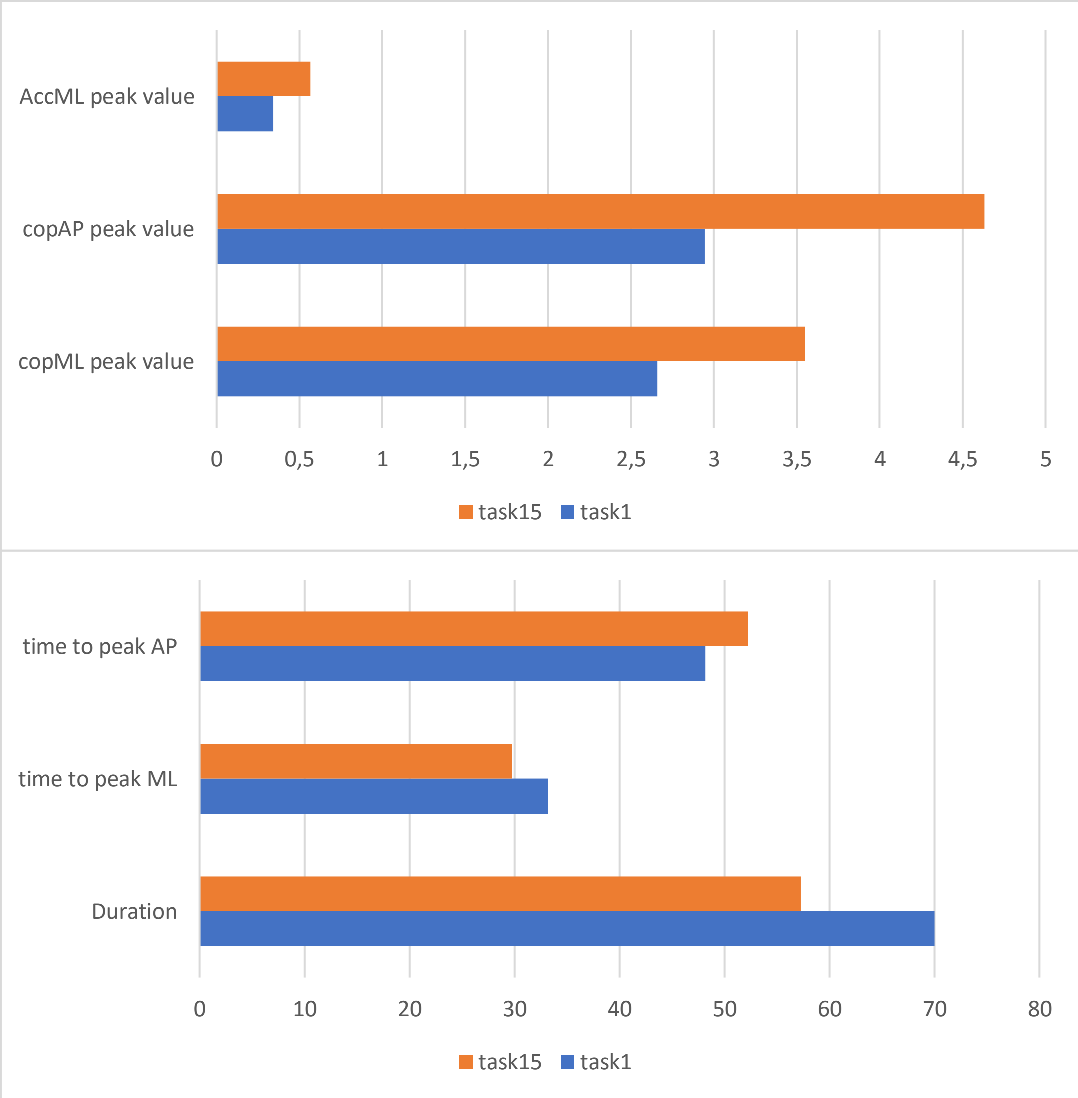


Figure 35

A cognitive task causes effects similar to task 13 and 12: an increase in the duration of the APA with an increase in both mediolateral and anteroposterior peaks.

To sum up, it emerged **that the speed of execution and the number of steps modify the duration of the APA and the value of the CoP peaks. Varying the length of the step has almost exclusively influenced the values of the CoP peaks. It is interesting to note how varying the reaction time, inserting cognitive tasks and performing the task with eyes closed has all led to a decrease in duration and time-to-peak and an increase in ML and AP peaks.**

8.2 Overall Analysis

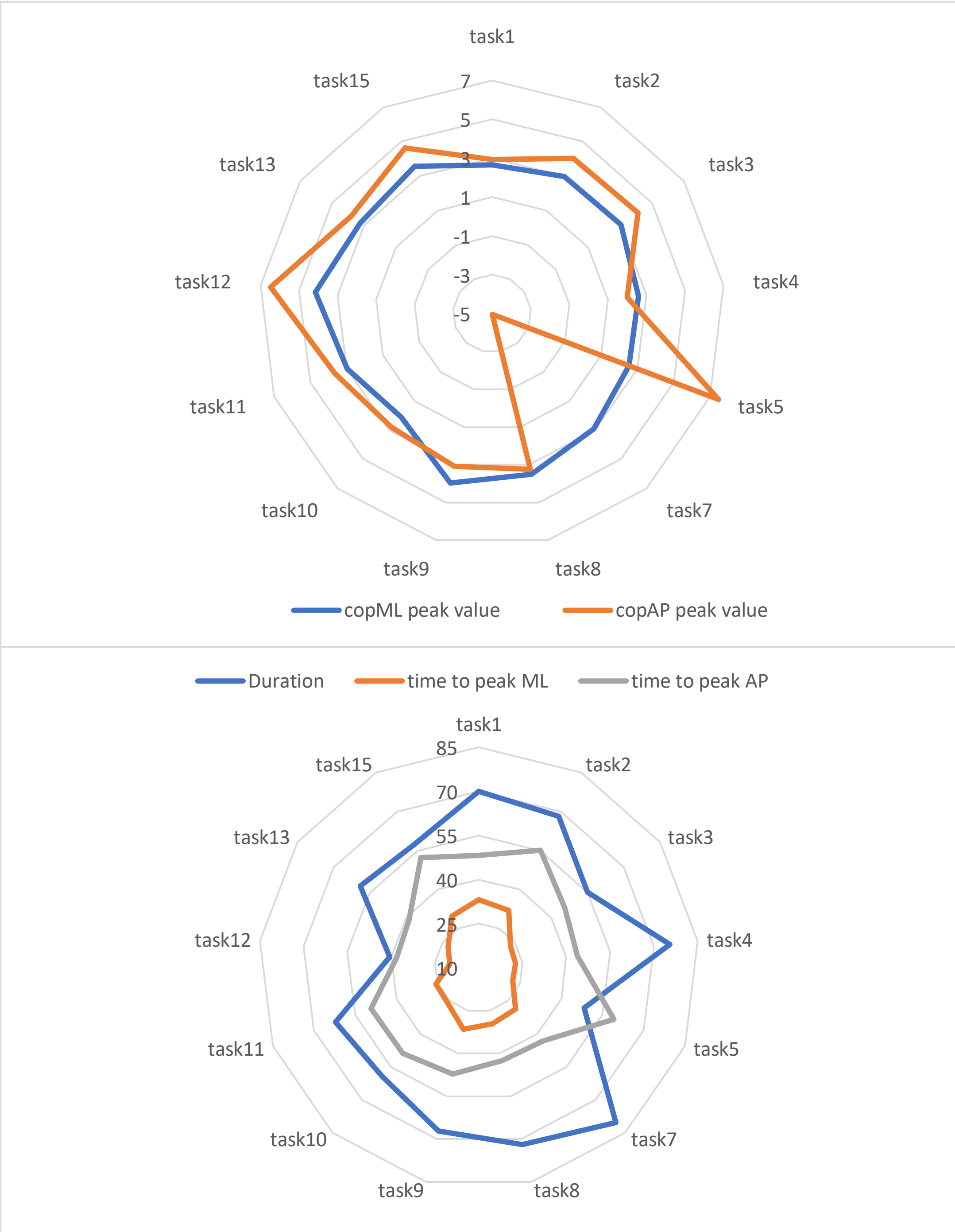


Figure 36

For a better comparison, data with the same unit of measure are plotted together in a radar graph. These graphs allow you to observe which tasks and which variables are the most sensitive to the tests performed.

Task 5 (fast step) and 12 (short reaction time) are the highest in terms of CoP AP peak but, at the same time, they have the shortest APAs. In terms of time to peak AP the tasks have completely different behaviour: task 5 presents the highest value while task 12 has the shortest one. To sum up, the speed and the reaction time of the task are two of the most influential variables regarding to the APAs prior step.

Task 4 (slow step) and 7 (backward step) have the longest APA while all other parameters are average. The reason why this happens is thought to be related to the fact that the movement is not usual especially for task 7, when the subject's gaze is not in the direction of gait progression.

It is also noteworthy that the time required to reach the average lateral peak is always less than the time to peak AP as if an event followed the other.

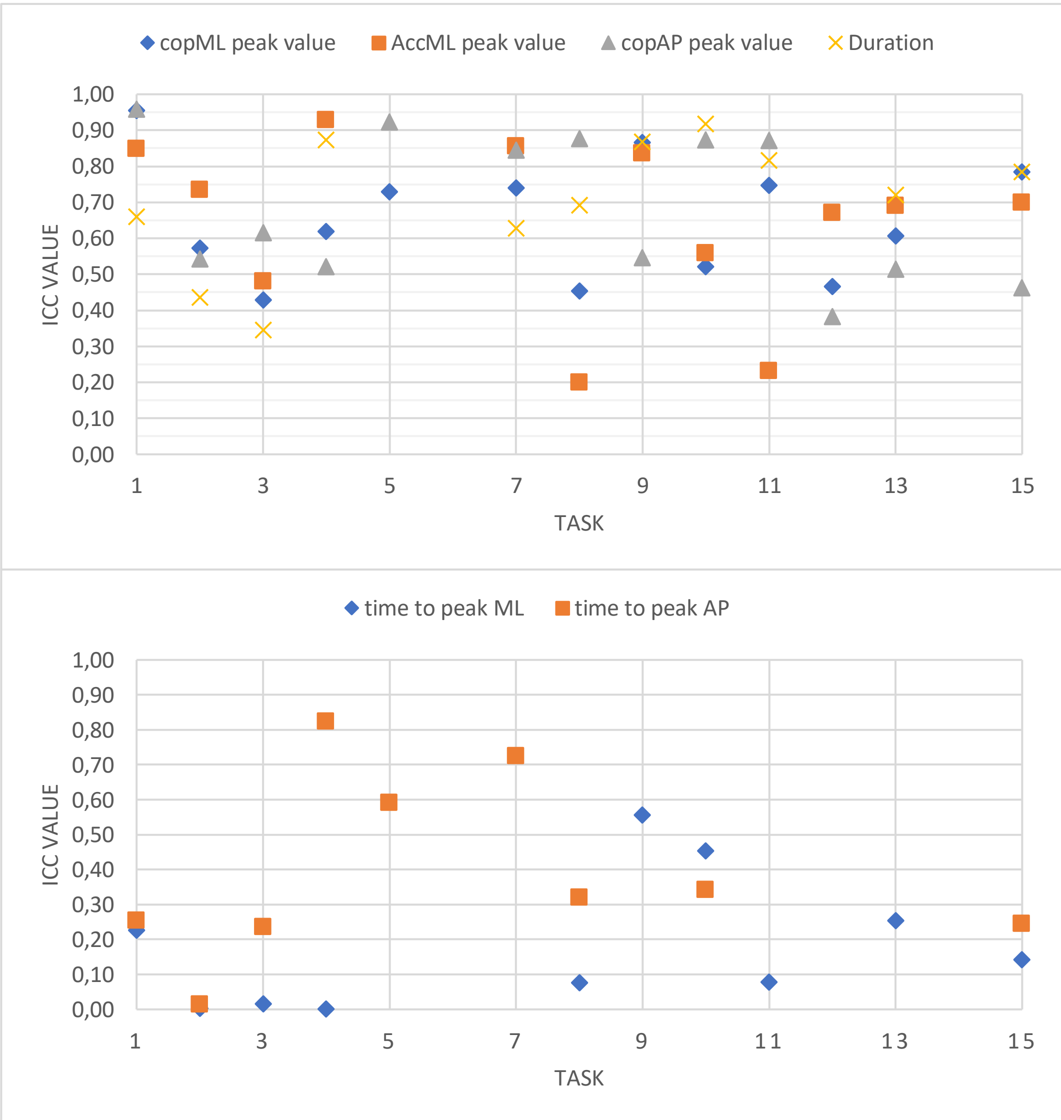


Figure 37

Only in the case of task 5 the anteroposterior peak occurs even after the toe off. This is probably due to the speed of the movement, i.e. the movement is so fast that it cannot reach the anteroposterior peak before the heel comes off the ground.

In the Figure 37 we report the ICC values obtained for each task. It is noteworthy that the duration and the acceleration and CoP peaks have ICC often greater than 0.4. In particular, the ICCs of the CoP AP and CoP ML in most cases are even higher than 0.75; this means that there is high similarity between the trials of the same subject. Instead, the time to peak CCIs are for the most part lower than the minimum value.

Overall, the peak and overall duration parameters are reliable and repeatable for the same subject. These are values that can be taken into consideration for future studies.

8.3 LIMITS AND FUTURE DEVELOPMENTS

The present study has some limitations, mostly in terms of sample size and algorithm development.

The analysed population consisted of only 5 subjects aged between 20 and 25 years. The female subjects were only 1. From a statistical point of view a larger and more diverse population in age and sex would have been more representative. The algorithms built for the analysis of the anteroposterior acceleration of the trunk (based on a trigger equal to baseline plus 2 standard deviations) did not allow to obtain enough results for the comparison between the tasks. Future experiments aimed at building a better algorithm suitable for studying this signal will be particularly useful in the overall analysis of anticipatory step movements.

Moreover, future studies could be aimed at studying the single variables (listed in the specific chapter) modulating their intensity and seeing how anticipatory movements respond.

9 BIBLIOGRAPHY

1. Yiou, E., Caderby, T., Delafontaine, A., Fourcade, P. & Honeine, J.-L. Balance control during gait initiation: State-of-the-art and research perspectives. *World Journal of Orthopedics* **8**, 815–828 (2017).
2. Influence of gait speed on the control of mediolateral dynamic stability during gait initiation | Elsevier Enhanced Reader. doi:10.1016/j.jbiomech.2013.11.011
3. MacKinnon, C. D. *et al.* Preparation of Anticipatory Postural Adjustments Prior to Stepping. *Journal of Neurophysiology* **97**, 4368–4379 (2007).
4. Varghese, J. P., Merino, D. M., Beyer, K. B. & McIlroy, W. E. Cortical control of anticipatory postural adjustments prior to stepping. *Neuroscience* **313**, 99–109 (2016).
5. Chang, W.-H. Role of the premotor cortex in leg selection and anticipatory postural adjustments associated with a rapid stepping task in patients with stroke. 7 (2010).
6. Jacobs, J. V., Lou, J. S., Kraakevik, J. A. & Horak, F. B. THE SUPPLEMENTARY MOTOR AREA CONTRIBUTES TO THE TIMING OF THE ANTICIPATORY POSTURAL ADJUSTMENT DURING STEP INITIATION IN PARTICIPANTS WITH AND WITHOUT PARKINSON'S DISEASE. 9 (2009).
7. Richard, A. *et al.* Contribution of the supplementary motor area and the cerebellum to the anticipatory postural adjustments and execution phases of human gait initiation. *Neuroscience* **358**, 181–189 (2017).
8. Timmann, D. & Horak, F. B. Perturbed step initiation in cerebellar subjects: 2. Modification of anticipatory postural adjustments. 11
9. Lu, C., Huffmaster, S. L. A., Harvey, J. C. & MacKinnon, C. D. Anticipatory postural adjustment patterns during gait initiation across the adult lifespan. 14 (2018).
10. Sousa, A. S. P., Silva, A. & Santos, R. Ankle anticipatory postural adjustments during gait initiation in healthy and post-stroke subjects. *Clinical Biomechanics* 6 (2015).

11. Buckley, T. A., Oldham, J. R., Munkasy, B. A. & Evans, K. M. Decreased Anticipatory Postural Adjustments During Gait Initiation Acutely Postconcussion. *Archives of Physical Medicine and Rehabilitation* **98**, 1962–1968 (2017).
12. Khanmohammadi, R., Talebian, S., Hadian, M. R., Olyaei, G. & Bagheri, H. Preparatory postural adjustments during gait initiation in healthy younger and older adults: Neurophysiological and biomechanical aspects. *Brain Research* **1629**, 240–249 (2015).
13. Bonora, G. *et al.* Gait initiation is impaired in subjects with Parkinson's disease in the OFF state: Evidence from the analysis of the anticipatory postural adjustments through wearable inertial sensors. *Gait & Posture* **51**, 218–221 (2017).
14. Rocchi, L., Mancini, M., Chiari, L. & Cappello, A. Dependence of Anticipatory Postural Adjustments for Step Initiation on Task Movement Features: A Study Based on Dynamometric and Accelerometric Data. 4
15. M Mancini, P Carlson-Kuhta, L Chiari & F B Horak. Anticipatory postural adjustments prior to step initiation are hypometric in untreated ParkinsonÕs disease: an accelerometer- based approach. 7 (2009).
16. Shiratori, T. Anticipatory postural adjustments associated with a loading perturbation in children with hemiplegic and diplegic cerebral palsy. *Exp Brain Res* 12 (2016).
17. Slijper, H., Latash, M. L., Rao, N. & Aruin, A. S. Task-specific modulation of anticipatory postural adjustments in individuals with hemiparesis. *Clinical Neurophysiology* 14 (2002).
18. Bonora, G. *et al.* Investigation of Anticipatory Postural Adjustments during One-Leg Stance Using Inertial Sensors: Evidence from Subjects with Parkinsonism. *Front. Neurol.* **8**, 361 (2017).
19. Adkin, A. L., Frank, J. S., Carpenter, M. G. & Peysar, G. W. Fear of falling modifies anticipatory postural control. *Exp Brain Res* **143**, 160–170 (2002).
20. Aruin, A. & Shiratori, T. Anticipatory postural adjustments while sitting: The effects of different leg supports. *Experimental Brain Research* **151**, 46–53 (2003).

21. Aruin, A. S., Ota, T. & Latash, M. L. Anticipatory postural adjustments associated with lateral and rotational perturbations during standing. *Journal of Electromyography and Kinesiology* 13 (2001).
22. Santos, M. J., Kanekar, N. & Aruin, A. S. The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. *Journal of Electromyography and Kinesiology* **20**, 388–397 (2010).
23. Santos, M. J., Kanekar, N. & Aruin, A. S. The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. *Journal of Electromyography and Kinesiology* **20**, 398–405 (2010).
24. Esposti, R., Bruttini, C., Bolzoni, F. & Cavallari, P. Anticipatory Postural Adjustments associated with reaching movements are programmed according to the availability of visual information. *Experimental Brain Research* **235**, 1349–1360 (2017).
25. Ferrari, A., Tersi, L., Ferrari, A., Sghedoni, A. & Chiari, L. Functional reaching discloses perceptive impairment in diplegic children with cerebral palsy. 6 (2010).
26. van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G. & van Cingel, R. E. H. How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS One* **12**, (2017).
27. Mancini, M., Chiari, L., Holmstrom, L., Salarian, A. & Horak, F. B. Validity and reliability of an IMU-based method to detect APAs prior to gait initiation. *Gait & Posture* **43**, 125–131 (2016).