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ÁREA DE BIOINGENIERÍA DE LA REHABILITACIÓN

UNA INVESTIGACIÓN MULTI-SENSOR DE LOS AJUSTES POSTURALES ANTICIPATORIOS EN LA INICIACIÓN DE MOVIMIENTOS VOLUNTARIOS

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1.- INTRODUCCIÓN Y OBJETIVO

Desde el momento en que nacemos comenzamos a descubrir cómo movernos por el mundo. Durante los primeros años de nuestra vida empezamos a desarrollar nuestras habilidades locomotrices, las cuales seguimos entrenando y refinando hasta la edad adulta. Estas habilidades locomotrices son la base del movimiento humano e incluyen caminar, correr o saltar. En nuestro día a día necesitamos ejecutar tareas que requieren una cierta coordinación además de la posibilidad o habilidad física de desarrollarlas. Algunos ejemplos de estas actividades que debemos afrontar cada día son subir escaleras, caminar o levantarnos de una silla.

Debido a la importancia en nuestra vida diaria (entre otras razones), el sistema locomotor humano y sus funciones ha sido un interesante tema de estudio desde hace varios siglos. Estos estudios han variado dependiendo de la tecnología disponible en cada época. Hoy en día, gracias al desarrollo de la tecnología e instrumentación, estamos en grado de estudiar aspectos de la función locomotora que hace solo algunos años hubieran sido inimaginables.

1.1.- Ajustes posturales anticipatorios (APA's)

Antes de comenzar a caminar, el cuerpo necesita ejecutar una transición desde una postura parada apoyada en ambas piernas hacia un equilibrio dinámico que permita el movimiento del cuerpo hacia delante [10]. El proceso de inicio del paso está compuesto de una fase preparatoria y del comienzo del paso en sí.

Durante la primera fase los ajustes posturales anticipatorios (anticipatory postural adjustments) aparecen. Comprenden un cambio en la posición del centro de masa (CoM) y el centro de presión (CoP) de nuestro cuerpo. Durante un paso normal, el desplazamiento del CoP sigue esta trayectoria: se mueve hacia atrás y hacia delante, así como primero hacia la pierna que se moverá y después hacia la pierna que se mantendrá parada al iniciar el paso (la pierna de apoyo). La segunda fase (el paso en sí), empieza cuando el peso ha sido transferido hacia la pierna de apoyo, dejando así la pierna móvil libre para avanzar. Como es definido en [14] "el inicio del paso es el fin de los APA's".

Es importante destacar que los APA's están presentes antes de todo tipo de movimiento voluntario, no solo antes de caminar. Algunos ejemplos de movimientos que comportan también APA's son levantar una pierna para estar a la pata coja, subir una escalera o inclinarse para alcanzar un objeto lejano. Los APA's varían también dependiendo de la inclinación del suelo [15], la postura [16], la edad [17] [18], la presencia de enfermedades neurodegenerativas como el Parkinson [19] o la enfermedad de Huntington [20], o si la persona ha sufrido un derrame cerebral o amputación [21].

Los APA's pueden ser definidos como los pre-movimientos de nuestro cuerpo (cambios en la postura) que tienen lugar antes del movimiento principal. El objetivo de los APA's es balancear y preparar nuestro cuerpo (cambiando la posición del CoP y del CoM) para alcanzar un equilibrio dinámico que nos permita ejecutar el movimiento siguiente. Estos movimientos son relativamente pequeños y no pueden ser apreciados por el ojo humano; su estudio requiere de la instrumentación adecuada.

Las investigaciones sobre los APA's han aumentado su importancia en los últimos años ya que varios estudios han probado que es una herramienta poderosa para evaluar y detectar diferentes fases de varias enfermedades neurodegenerativas [22] [23].

Dentro de estas enfermedades neurodegenerativas, la cual cuyos APA's han sido más estudiados es la enfermedad de Parkinson (PD). Se ha demostrado que el estudio de los APA's es útil para detectar PD en etapas tempranas, cuando incluso puede no haber evidencias clínicas detectables [22]. Además, existen varios tipos diferentes de estudios relacionando los APA's y el PD: estudios comparando pacientes tomando o no levodopa [10] o experimentos analizando diferentes movimientos como subir escalones [23] o pasos normales [10] [22].

En cuanto a los métodos experimentales e instrumentación utilizada, el setup experimental clásico utiliza una plataforma de fuerza y (en los últimos años) acelerómetros. En los estudios más recientes han sido usados incluso smartphones [24]. Como fue mencionado anteriormente, los APA's son movimientos relativamente pequeños y no pueden ser caracterizados adecuadamente con videocámaras. Las ventajas de los acelerómetros comparados con la plataforma de fuerza es que son baratos y portátiles. La plataforma de fuerza es un sensor más fiable y preciso, pero su precio es mucho más alto que el de los acelerómetros y a menudo requiere de un laboratorio de análisis de movimiento. Además, los acelerómetros pueden ser usados en cualquier lugar debido a su pequeño tamaño y sistema de transferencia de datos sin cables. No hace falta tener un laboratorio perfectamente equipado para utilizarlos; solo es necesario un ordenador con el software adecuado y suficiente espacio para ejecutar los movimientos a estudiar.

1.2.- Propósito del estudio

El estudio tiene 2 objetivos principales. El primero de ellos es desarrollar un protocolo experimental que sirva para estudios similares en un futuro. El segundo de ellos es, utilizando este protocolo experimental, analizar los APA's durante varios movimientos típicos de nuestro día a día. Se han comparado los APA's de 10 movimientos diferentes comenzando desde 4 configuraciones iniciales diferentes. La cuatro configuraciones iniciales han sido open eyes/closed legs (OE/CL), open eyes/open legs (OE/OL), closed eyes/closed legs (CE/CL) y closed eyes/open legs (CE/OL).

Es interesante analizar el efecto de la distancia entre los talones antes de iniciar el movimiento ya que, como se puede ver en otros estudios similares, no hay una distancia estándar entre talones para estudiar los APA's. Algunos estudios fijan la distancia [22] [25] mientras que otros dejan al sujeto estar en una posición cómoda a su elección [23] [26]

[27]. En cuanto a las diferencias en los APA’s con ojos abiertos o cerrados, el objetivo es ver la influencia de los diferentes inputs sensoriales en los APA’s.

Para el estudio se han utilizado una plataforma de fuerza, 2 acelerómetros y un sistema de plantillas detectoras de presión. La plataforma de fuerza es un estándar para estudios de APA’s y análisis del camino. Los acelerómetros han sido utilizados durante los últimos años para analizar los APA’s, ya que son baratos y portables. El sistema de plantillas detectoras de presión no es muy típico en este tipo de estudios, y proporciona información diferente que los otros sensores.

Se han calculado parámetros típicamente utilizados en estos estudios (buscados en la bibliografía) con el objeto de comparar el efecto de las 4 configuraciones iniciales diferentes.

2.- MÉTODOS

2.1.- Participantes

Tres sujetos sanos han participado en el estudio. Las edades han estado comprendidas en un rango de 24 a 30 años y las alturas entre 1.65 y 1.77 metros.

2.2.- Instrumentación utilizada

Los participantes han utilizado 2 unidades IMU EXLs3. Se ha utilizado para ambos sensores una frecuencia de muestreo de 100 Hz y se han transmitido los datos vía Bluetooth a un PC localizado en la misma sala para su posterior análisis offline. Un fondo escala de ±2 g se ha utilizado para aprovechar al máximo la resolución de los sensores en esta aplicación. Se ha utilizado solo la información obtenida por los acelerómetros de las unidades IMU. Los datos obtenidos por el giroscopio y la brújula no se han utilizado.

Se ha situado uno de los acelerómetros en la espalda, cerca de la vértebra L5 utilizando el cinturón del sistema Pedar. Esta posición para el acelerómetro ha sido utilizada en estudios similares [22] [25] [33] [34] [35] porque se encuentra cerca del centro de masa del cuerpo.

El segundo acelerómetro se ha situado cerca de la vértebra C7 utilizando cinta adhesiva. Esta posición ha sido elegida también teniendo en cuenta otros estudios [22]. Sin embargo, como es comentado en [1], debido al movimiento impredecible de la cabeza durante el experimento las medidas obtenidas por este acelerómetro no son 100% fiables y deben ser tenidas en cuenta muy cuidadosamente.

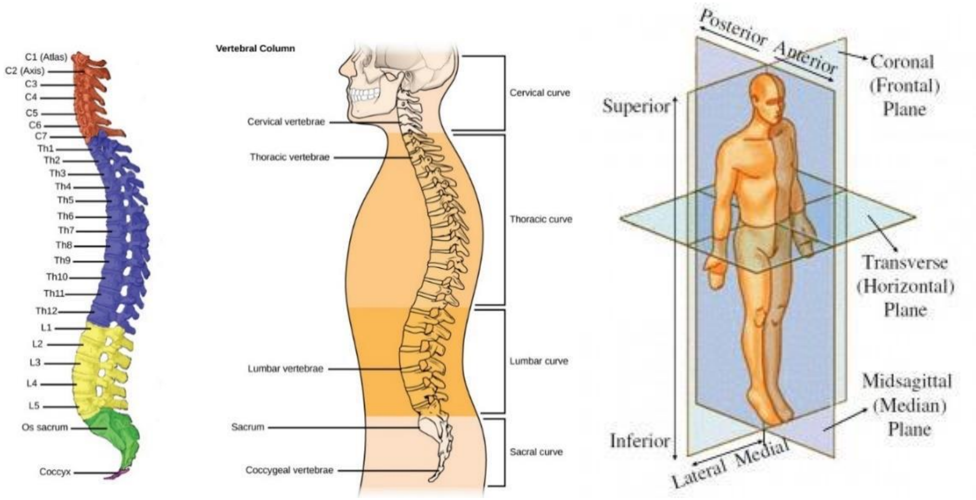

Fig. 2.2.1 y 2.2.2. Posición de las vértebras y direcciones del cuerpo

Los ejes de medida de los 2 acelerómetros han sido paralelos. Los ejes X, Y y Z se orientaron a lo largo de las direcciones del cuerpo medio-lateral (ML), vertical y antero-posterior (AP) respectivamente.

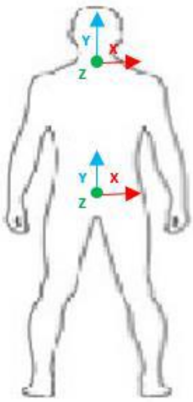

Fig. 2.2.3. Ejes de medida de los acelerómetros

Por otra parta, se ha utilizado una plataforma de fuerza Bertec Legacy para medir la ground reaction force y el desplazamiento del CoP en las direcciones medio-lateral y antero-posterior. Se ha conectado vía USB al ordenador del laboratorio. La frecuencia de muestreo utilizada ha sido de 1 kHz. Como los otros sensores utilizaban una frecuencia de muestreo de 100 Hz, la información obtenida por la plataforma de fuerza se ha re-sampleado offline. Se han situado marcadores/indicadores visuales en la plataforma de fuerza para ayudar a los sujetos a posicionar los pies en la posición requerida.

El sistema Pedar se ha utilizado para medir diferentes parámetros de los pies del sujeto. Se ha utilizado una frecuencia de muestreo de 100 Hz (la misma que para los acelerómetros). El sistema se ha fijado al sujeto utilizando sus propios accesorios. Como pequeño resumen del sistema de fijación, se ha situado la CPU portátil en el cinturón Pedar y se han situado las plantillas entre las zapatillas de deporte y los calcetines del sujeto. Se ha almacenado la información obtenida en una tarjeta SD insertada en la CPU para su posterior análisis offline.

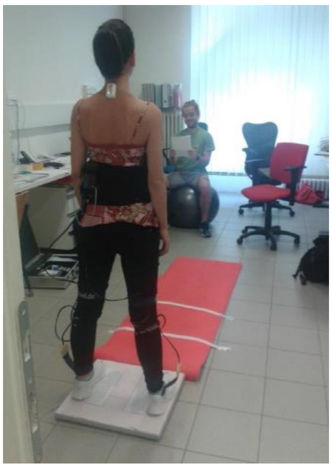

Fig. 2.2.4. Setup experimental

2.3.- Protocolo experimental

Se ha dividido el procedimiento experimental en 2 partes. La primera tenía el único objetivo de sincronizar la señal de los 4 sensores diferentes. Durante la segunda parte los participantes han completado los movimientos previamente programados.

2.3.1.- Sincronización

Debido a la imposibilidad de iniciar la adquisición de datos de los 4 sensores al mismo tiempo surge la necesidad de sincronizar las señales. La plataforma de fuerza utiliza su propio software para iniciar la adquisición de datos, al igual que los acelerómetros. Además, el sistema Pedar inicia a registrar información a través de un control remoto. Ya que era imposible empezar la adquisición de datos a la vez de todos los sensores, una rutina fue definida que permitía sincronizar en el tiempo las señales provenientes de los 4 sensores.

Primero, se iniciaba el software de los 3 tipos de sensores diferentes en el ordenador del laboratorio. La plataforma de fuerza y el sistema Pedar se calibraban inmediatamente después de este primer paso. Después, se situaba la plantilla derecha del sistema Pedar sobre la plataforma de fuerza. Más tarde, se situaban los acelerómetros encima de la plantilla del sistema Pedar, formando todos los sensores una pequeña pila. Una vez que todos los sensores estaban unos encima de otros, se iniciaba la adquisición de datos de todos ellos, utilizando sus diferentes softwares y el control remoto del sistema Pedar: primero los acelerómetros, luego la plataforma de fuerza y por último el sistema Pedar.

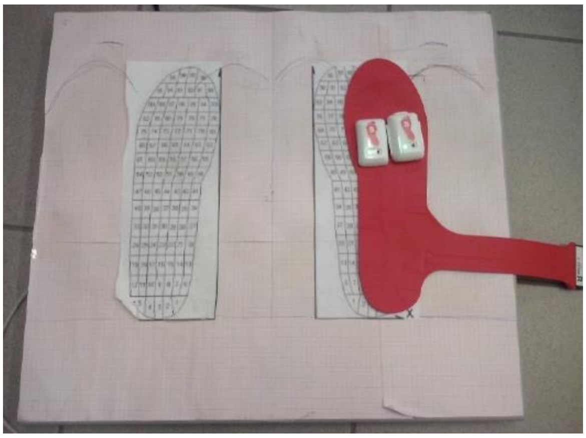

Fig. 4.3.1. Disposición de los sensores antes de golpearlos

Cuando todos los sensores estaban recogiendo datos y situados uno encima del otro, se les golpeaba breve pero firmemente. El objetivo de este golpe era tener un pico en las señales de los 4 sensores que permitiría después sincronizar estas señales utilizando un código Matlab especialmente diseñado.

2.3.2.- Movimientos

Los sujetos han realizado 10 movimientos diferentes para analizar sus APA's. Los movimientos y su orden de ejecución están explicados en la Tabla 2.3.1.

Número	Movimiento
1	Paso corto empezando con la pierna derecha
2	Paso largo empezando con la pierna derecha
3	Paso corto empezando con la pierna izquierda
4	Paso largo empezando con la pierna izquierda
5	Paso atrás empezando con la pierna derecha
6	Paso atrás empezando con la pierna izquierda
7	Aguantar solo con la pierna izquierda
8	Aguantar solo con la pierna derecha
9	Giro hacia la derecha
10	Giro hacia la izquierda

Tabla 2.3.1. Orden y descripción de los movimientos del experimento

Antes de comenzar el test definitivo y completo, los participantes han ejecutado un paso corto y uno largo con el objeto de tener un indicador de cómo sería un paso corto y largo "modelo". Se han colocado dos cintas a la distancia de ambos pasos con el objeto de mejor la repetitividad, dando a los participantes información visual sobre la longitud aproximada deseada de sus movimientos.

Fig. 2.3.2. Cintas colocadas para indicar la distancia de los pasos corto y largo

Después, los participantes han completado 10 movimientos comenzando desde 4 diferentes configuraciones iniciales. El orden de ejecución de los movimientos con estas configuraciones ha sido open eyes/closed legs (OE/CL), open eyes/open legs (OE/OL), closed eyes/closed legs (CE/CL) y closed eyes/open legs (CE/OL). Este orden esta esquematizado en la tabla 2.3.2. La distancia entre talones en las configuraciones de piernas cerradas era idealmente 0, mientras que en la posición de piernas abiertas 30 cm. La plataforma de fuerza contaba con signos e indicadores visuales para ayudar a los participantes a colocar los pies en la posición deseada.

	Open eyes (OE)	**Closed eyes (CE)**
Closed legs (CL)	1st	3rd
Open legs (OL)	2nd	4rd

Tabla 2.3.2. Orden de ejecución de las configuraciones iniciales

La ejecución de los 10 diferentes movimientos comenzando desde las 4 diferentes posiciones hace un total de 40 movimientos. El tiempo total de cada test fue de unos 15 minutos.

Antes de cada movimiento, el sujeto permanecía en la plataforma de fuerza con la pertinente configuración, sus brazos libres y mirando al frente. El sujeto debía contar hasta 5 (aproximadamente 5 segundos). Esta espera antes de ejecutar cada movimiento era necesaria para estabilizar el cuerpo (y por consiguiente el CoP) para después poder apreciar mejor los APA's.

Después de estos 5 segundos de espera los participantes recibían una orden vocal por parte del experimentador, indicando el movimiento que se les pedía ejecutar. Después de cada movimiento, el sujeto volvía a la plataforma de fuerza para continuar con el resto de movimientos siguiendo el mismo procedimiento.

2.4.- Análisis de datos

Como cada uno de los 3 tipos de sensores utilizaba un software diferente, los datos de cada uno se han extraído a documentos de texto para su posterior tratamiento con Matlab.

La frecuencia de muestreo de la plataforma de fuerza era 1 kHz por lo que fue re-sampleada a 100 Hz, la frecuencia usada por los otros 3 dispositivos.

Debido a algunas interferencias en el sistema Bluetooth, se perdían algunos paquetes de datos de los acelerómetros. Se ha creado y utilizado un código Matlab para interpolar los datos correspondientes a los paquetes perdidos.

Se ha realizado la sincronización utilizando también un código Matlab especialmente diseñado. El código tiene en cuenta el número de muestra correspondiente al instante cuando el pico (causado al golpear el sensor) aparece en la señal de cada uno de los 4 sensores. Utilizando esta información, se han recortado las señales de los acelerómetros y la plataforma de fuerza. La única señal que se ha mantenido su longitud original ha sido la del sistema Pedar.

Se ha identificado el comienzo de los APA's de los 40 movimientos utilizando el método usado en [22] [23] [24]. Se ha calculado la desviación estándar del CoP en la dirección medio-lateral durante la fase de espera antes de ejecutar el movimiento. Se ha definido el valor umbral como el doble de esta desviación estándar en cada movimiento. Cuando el desplazamiento del CoP medio-lateral alcanzaba este valor umbral, quería decir que los APA's habían comenzado. Todos los momentos de inicio de APA's definidos por este algoritmo se han comprobado visualmente. El final de los APA's se ha definido como el momento en el que el CoP medio-lateral volvía a su valor base.

Se han calculado diferentes parámetros utilizados en la bibliografía y serán comentados en el capítulo resultados y conclusiones.

3.- RESULTADOS Y CONCLUSIONES

3.1.- La fiabilidad del método de detección de APA's basado en la SD depende de la configuración inicial

La desviación estándar media de la posición del CoP medio-lateral durante todas las fases de espera (antes de los movimientos) ha sido calculada. Los resultados se pueden ver en la Figura 3.1.1.

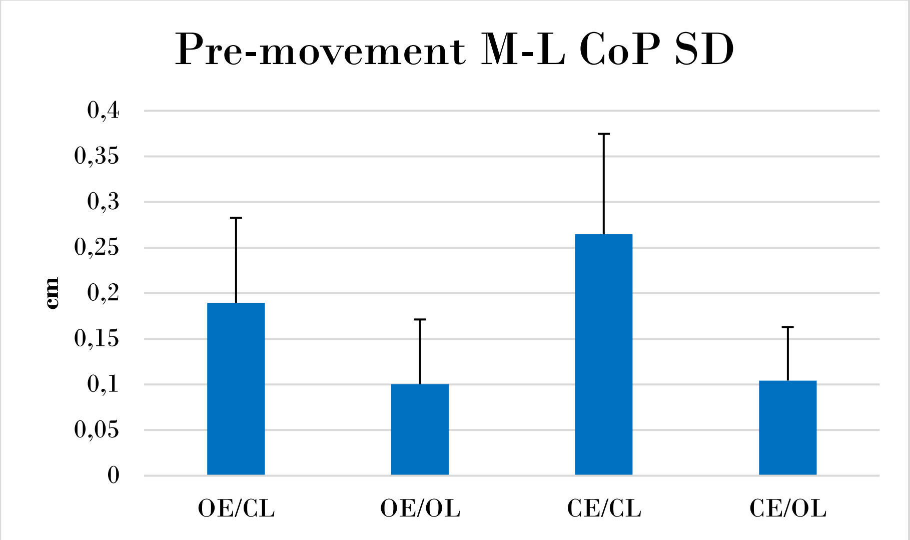

Fig. 3.1.1. Desviación estándar media del CoP M-L en las fases de espera pre-APA's

A pesar de la alta dispersión en los valores, se puede apreciar que la variación de la posición medio-lateral del CoP depende de la configuración inicial. Comparando las posiciones con piernas abiertas o cerradas, la posición con piernas juntas da menos estabilidad al cuerpo y por tanto la desviación estándar del CoP M-L es mayor (varíamos mas la posición del CoP). Por otra parte, no es fácil apreciar el efecto de la percepción visual en nuestro estudio. Los resultados con ojos abiertos y ojos cerrados son similares y por tanto no podemos concluir que la percepción visual influencie la variación del CoP medio-lateral durante la fase de espera que precede a los APA's y el movimiento.

Esta variación en la desviación estándar a causa de la posición de las piernas puede ser un problema al usar el método de detección de APA's utilizado en este y otros estudios [22] [23] [24]. El método fija un valor umbral para detectar el inicio de los APA's igual al doble de la desviación estándar del CoP medio-lateral durante la fase de espera antes de los APA's y movimientos. Dependiendo de la configuración inicial (piernas abiertas o cerradas) este valor umbral puede ser mucho mayor/menor y por tanto la duración estimada de los APA's menor/mayor. La figura 3.1.2 muestra un ejemplo.

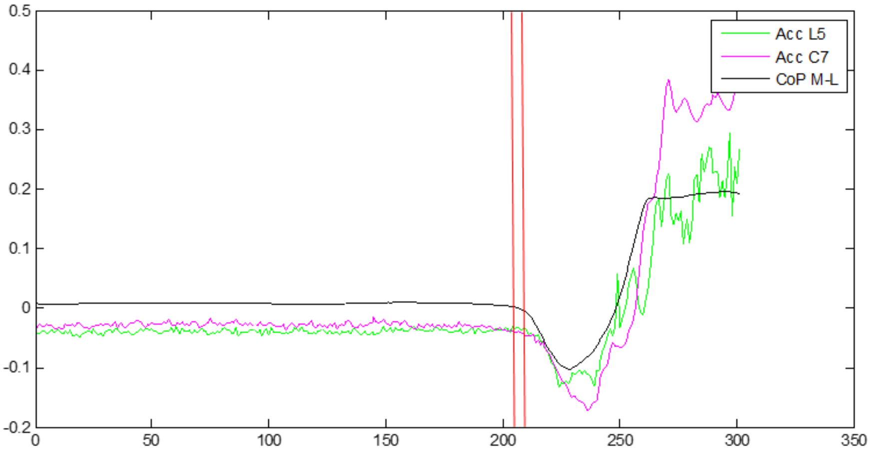

Fig. 3.1.2. Las líneas rojas indican diferentes momentos para definir el comienzo de los APA's dependiendo de la desviación standard utilizada

3.2.- La variación máxima de la fuerza en cada pie, la aceleración M-L pico y el máximo desplazamiento del CoP M-L varían dependiendo de la distancia inicial entre talones y no dependen de las condiciones visuales

La tabla 3.2.1 muestra la influencia de las configuraciones iniciales en diferentes parámetros comúnmente utilizados en este tipo de estudios.

	TTP	Peak force	Acc L5 M-L	Acc C7 M-L	CoP M-L	Acc L5 A-P	Acc C7 A-P	CoP A-P
Influenced by closed legs	Not clear	Yes	Yes	Yes	Yes	Not clear	Not clear	Not clear
Influenced by closed eyes	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear

Tabla 3.2.1. Influencia de la distancia entre talones y percepción visual en diferentes parámetros

3.3.- Los pasos largos tienen una aceleración pico y máximo desplazamiento del CoP mayores que los pasos cortos en las direcciones M-L y A-P

La aceleración pico media y el máximo desplazamiento del CoP medio han sido comparados en los pasos cortos y largos. Los datos obtenidos para los pasos con la izquierda así como con la derecha han sido utilizados para tener más información y poder llegar a una conclusión más fiable. La información obtenida por el acelerómetro en L5 ha sido utilizada ya que sus resultados son más fiables que los del acelerómetro en C7 [22]. Los resultados obtenidos y explicados más adelante coinciden con la conclusión obtenida en [36].

3.3.1.- Dirección medio-lateral

Se puede apreciar en la figura 3.3.1 que en 6 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) la aceleración M-L pico era más elevada cuando se ejecutaba el paso largo. Se puede concluir entonces que la aceleración M-L alcanza valores más elevados cuando se nos requiere realizar un paso más largo.

Por otra parte, se puede observar en la figura 3.3.2 que en 6 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) el desplazamiento del CoP M-L máximo era más elevado cuando se ejecutaba el paso largo. De nuevo, se puede concluir que el desplazamiento del CoP M-L máximo alcanza valores más elevados cuando se nos requiere realizar un paso más largo.

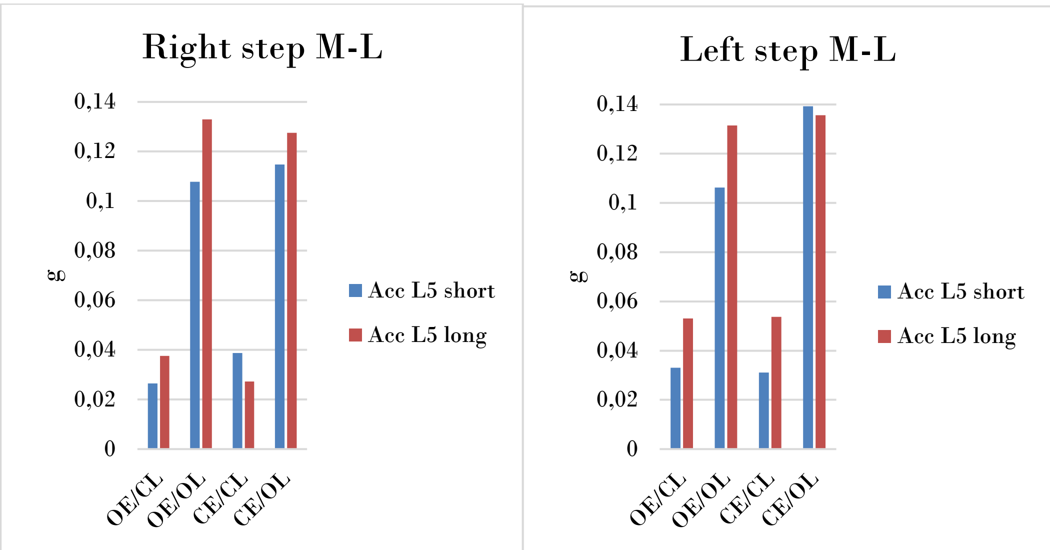

Fig. 3.3.1. Comparación de la aceleración pico M-L para pasos corto y largo

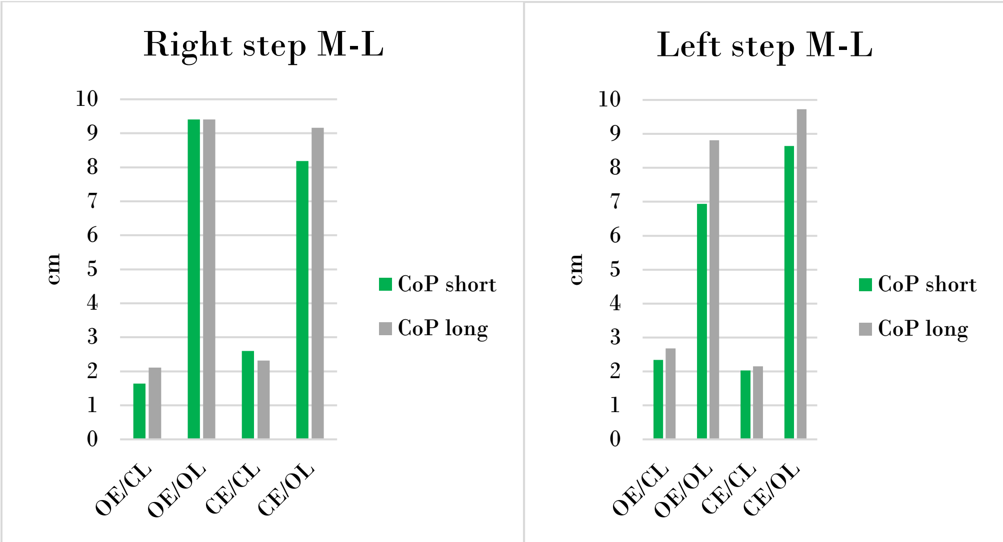

Fig. 3.3.2. Comparación de la máxima variación del CoP M-L para pasos corto y largo

3.3.2.- Dirección antero-posterior

El mismo procedimiento que para la dirección medio-lateral se ha seguido para la dirección antero-posterior.

Se puede apreciar en la figura 3.3.3 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) la aceleración A-P pico era más elevada cuando se ejecutaba el paso largo. Se puede concluir entonces que la aceleración A-P alcanza valores más elevados cuando se nos requiere realizar un paso más largo.

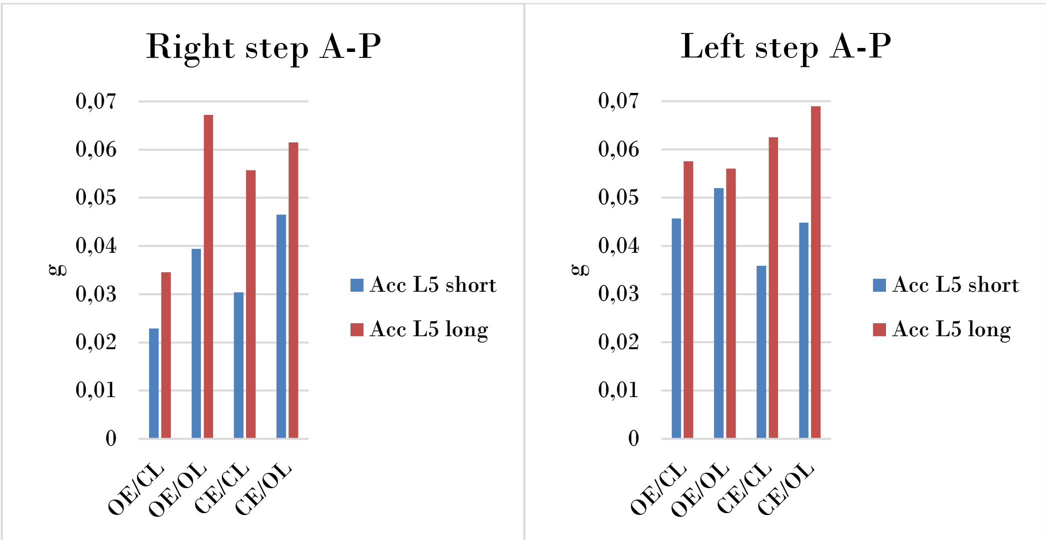

Fig. 3.3.3. Comparación de la aceleración pico A-P para pasos corto y largo

Por otra parte, se puede observar en la figura 3.3.4 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) el desplazamiento del CoP A-P máximo era más elevado cuando se ejecutaba el paso largo. De nuevo, se puede concluir que el desplazamiento del CoP A-P máximo alcanza valores más elevados cuando se nos requiere realizar un paso más largo.

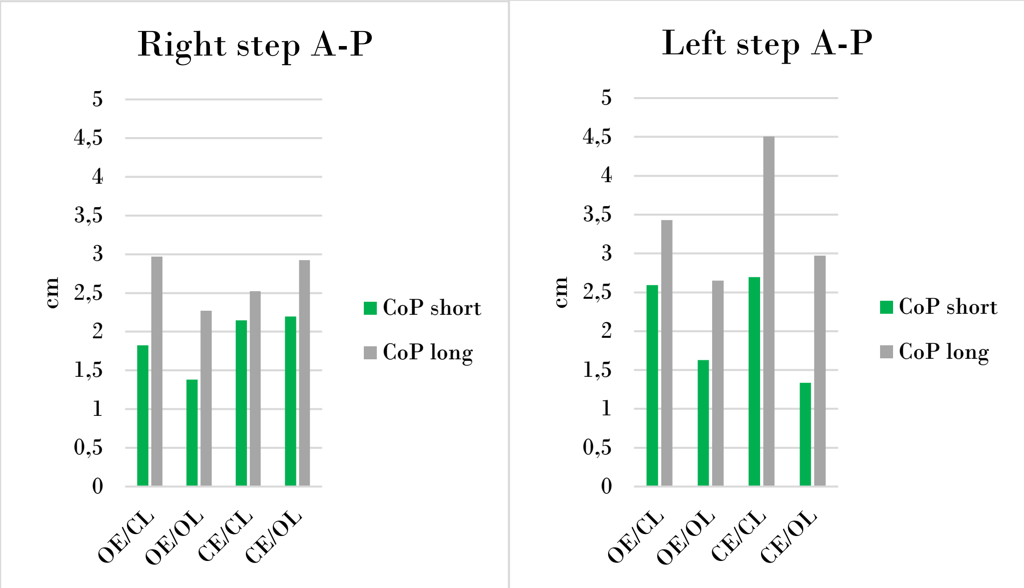

Fig. 3.3.4. Comparación de la máxima variación del CoP A-P para pasos corto y largo

Los resultados obtenidos coinciden con la aceptada interpretación biomecánica de los APA's y su relación directa con el movimiento siguiente. Más precisamente, cuanto mayor es el movimiento más grande son los picos en el APA en el desplazamiento del CoP y aceleración del cuerpo con el objeto de preparar mejor el cuerpo para una desestabilización potencial mayor.

3.4.- Los pasos con giro tienen una aceleración pico y máximo desplazamiento del CoP mayores que los pasos rectos en las direcciones M-L y A-P

La aceleración pico media y el máximo desplazamiento del CoP medio han sido comparados en los pasos con giro y rectos. Los datos obtenidos para los pasos con la izquierda así como con la derecha fueron utilizados para tener más información y poder llegar a una conclusión más fiable. La información obtenida por el acelerómetro en L5 ha sido utilizada.

3.4.1.- Dirección medio-lateral

Se puede apreciar en la figura 3.4.1 que en 6 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) la aceleración M-L pico era más elevada cuando se ejecutaba el paso con giro. Se puede concluir entonces que la aceleración M-L alcanza valores más elevados cuando se nos requiere realizar un paso con giro (comparando con un paso recto).

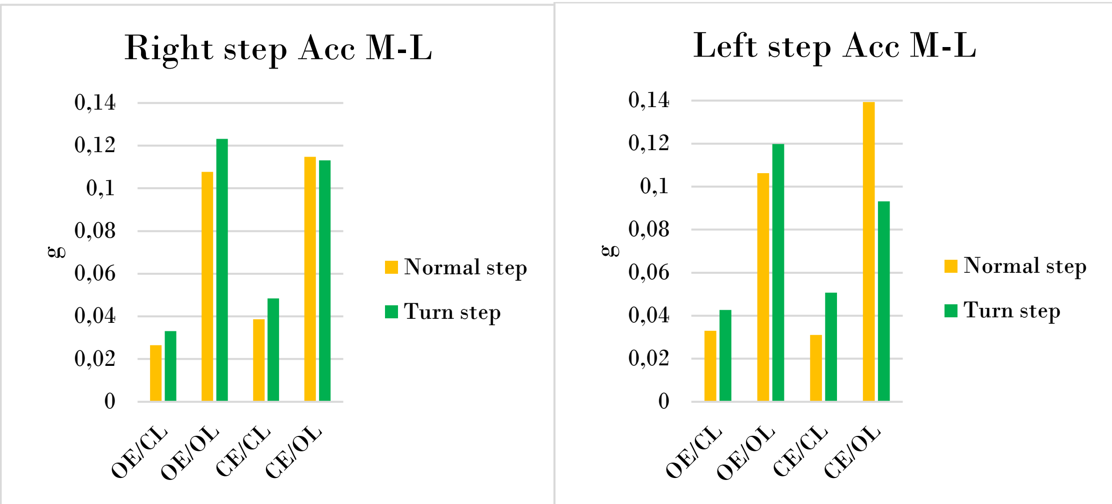

Fig. 3.4.1. Comparación de la aceleración M-L para pasos recto y con giro

Por otra parte, se puede observar en la figura 3.4.2 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) el desplazamiento del CoP M-L máximo era más elevado cuando se ejecutaba el paso con giro. De nuevo, se puede concluir que el desplazamiento del CoP M-L máximo alcanza valores más elevados cuando se nos requiere realizar un paso con giro.

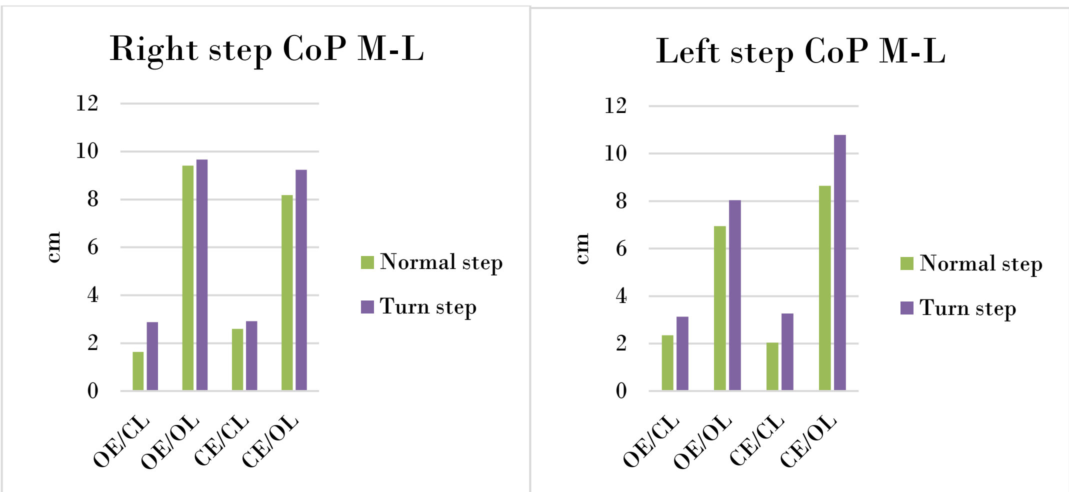

Fig. 3.4.2. Comparación de la máxima variación del CoP M-L para pasos recto y con giro

3.4.2.- Dirección antero-posterior

El mismo procedimiento que para la dirección medio-lateral se ha seguido para la dirección antero-posterior.

Se puede apreciar en la figura 3.4.3 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) la aceleración A-P pico fue era elevada cuando se ejecutaba el paso con giro. Se puede concluir entonces que la aceleración A-P alcanza valores más elevados cuando se nos requiere realizar un paso con giro.

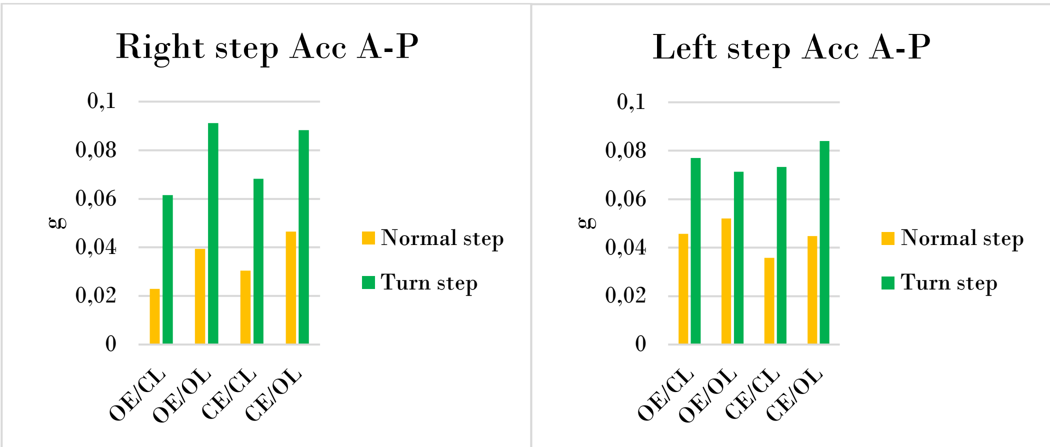

Fig. 6.4.3. Comparación de la aceleración A-P para pasos recto y con giro

Por otra parte, se puede observar en la figura 6.4.4 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) el desplazamiento del CoP A-P máximo era más elevado cuando se ejecutaba el paso con giro. De nuevo, se puede concluir que el desplazamiento del CoP A-P máximo alcanza valores más elevados cuando se nos requiere realizar un paso con giro.

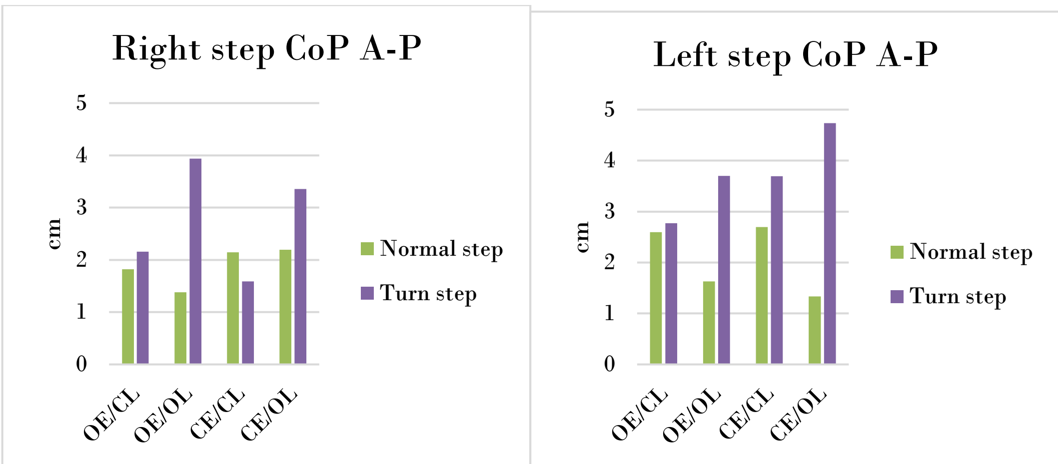

Fig. 3.4.4. Comparación de la máxima variación del CoP A-P para pasos recto y con giro

3.5.- El paso atrás tiene una aceleración pico y desplazamiento CoP máximo mayores que el paso adelante en la dirección A-P

La aceleración pico media y el máximo desplazamiento del CoP medio han sido comparados en los pasos hacia adelante y hacia atrás. Los datos obtenidos para los pasos con la izquierda así como con la derecha fueron utilizados para tener más información y poder llegar a una conclusión más fiable. La información obtenida por el acelerómetro en L5 ha sido utilizada.

3.5.1.- Dirección medio-lateral

Se puede apreciar en la figura 3.5.1 que, teniendo en cuenta los 8 diferentes casos (4 configuraciones y paso con la derecha o con la izquierda), no existe una aceleración claramente mayor en el paso adelante o en el paso hacia atrás.

Los resultados del desplazamiento CoP M-L maximo (figura 3.5.2) tampoco muestran una tendencia clara, siendo en algunos casos mayor para el paso hacia delante y en otros para el paso hacia atrás.

A la luz de estos resultados, no es posible concluir que el paso hacia atrás tenga claramente una mayor o menor aceleración M-L y desplazamiento CoP M-L máximo que el paso hacia delante.

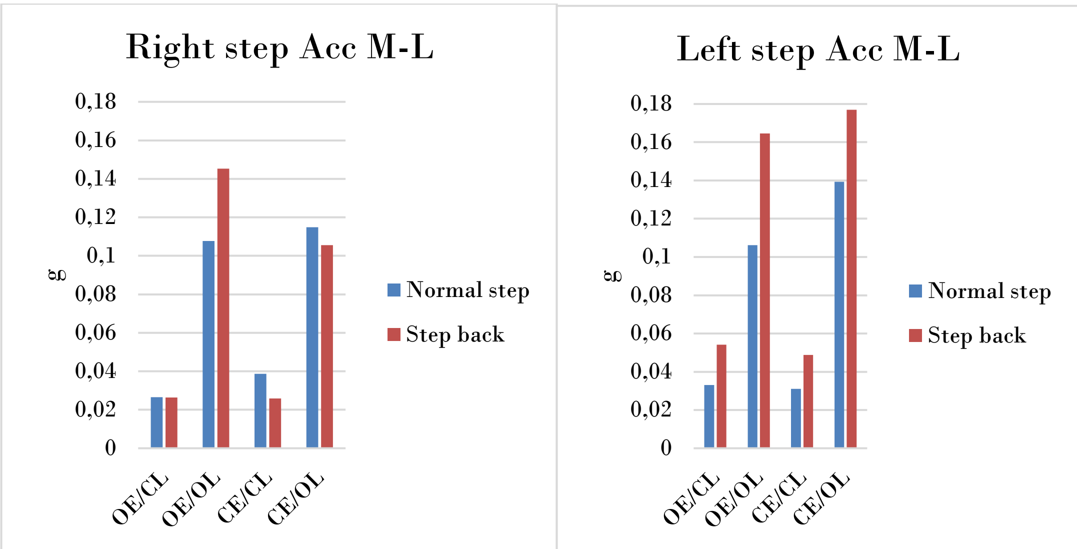

Fig. 3.5.1. Comparación de la aceleración M-L para pasos atrás y adelante

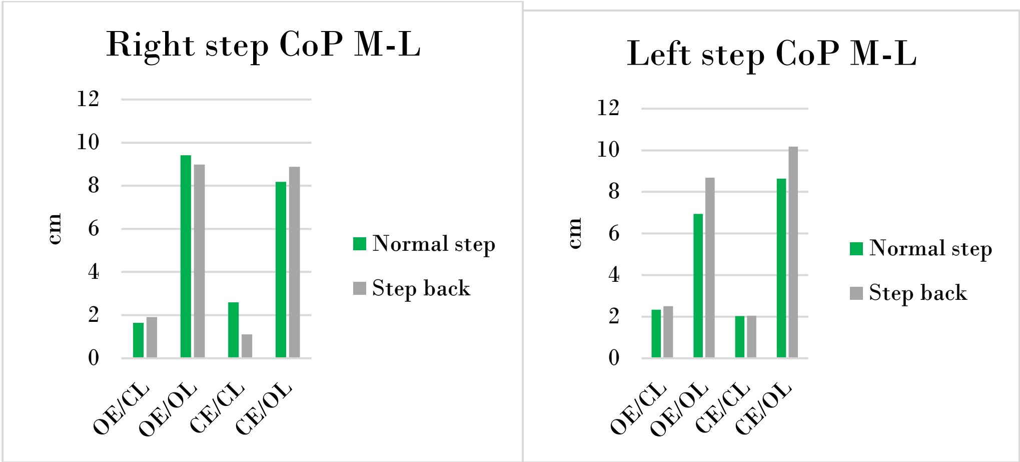

Fig. 3.5.2. Comparación de la máxima variación del CoP M-L para pasos adelante y atrás

3.5.2.- Dirección antero-posterior

El mismo procedimiento que para la dirección medio-lateral se ha seguido para la dirección antero-posterior.

Se puede apreciar en la figura 3.5.3 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) la aceleración A-P pico era más elevada cuando se ejecutaba el paso hacia atrás. Se puede concluir entonces que la aceleración A-P alcanza valores más elevados cuando se nos requiere realizar un paso hacia atrás.

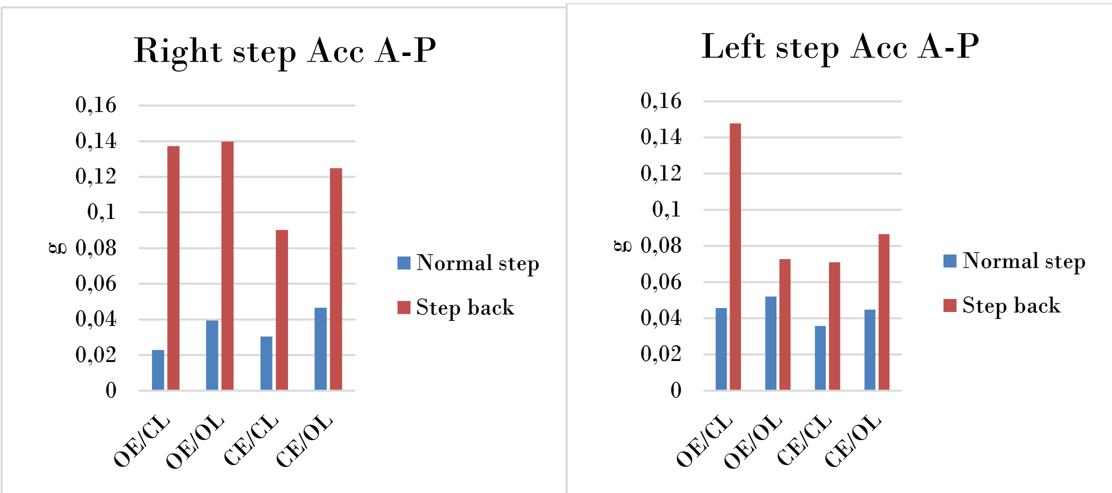

Fig. 3.5.3. Comparación de la aceleración A-P para pasos atrás y adelante

Por otra parte, se puede observar en la figura 3.5.4 que en 8 de los 8 casos diferentes (4 configuraciones iniciales diferentes y pasos con la derecha o con la izquierda) el desplazamiento del CoP A-P máximo era más elevado cuando se ejecutaba el paso hacia atrás. De nuevo, se puede concluir que el desplazamiento del CoP A-P máximo alcanza valores más elevados cuando se nos requiere realizar un paso hacia atrás (comparado con el paso hacia delante).

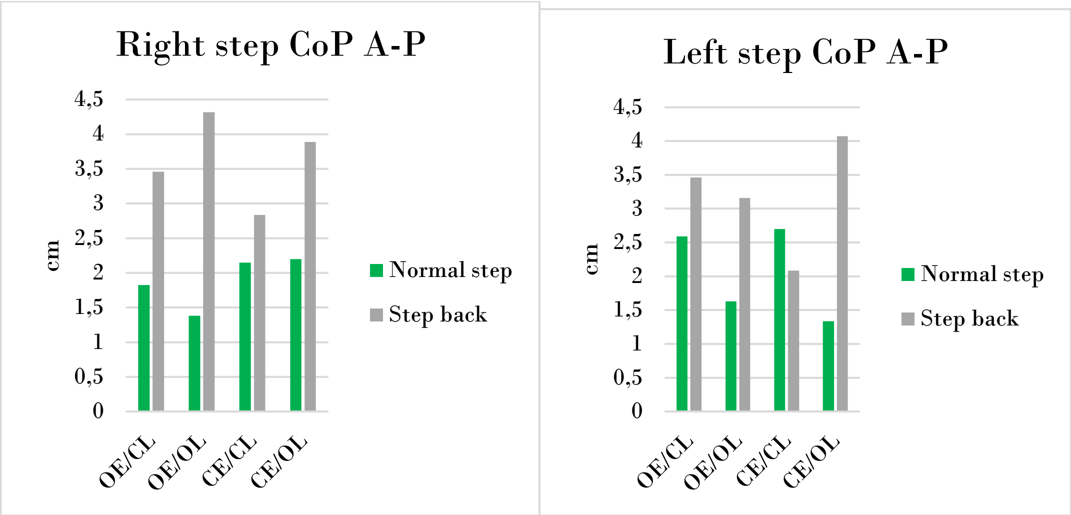

Fig. 3.5.4. Comparación de la máxima variación del CoP A-P para pasos adelante y atrás

Una de las razones por las que la aceleración A-P pico y el máximo desplazamiento del CoP A-P alcanza valores más elevados es que nuestro cuerpo tiene más superficie disponible en los pies para realizar el balanceo, comparado con el paso hacia delante. Cuando queremos ejecutar un paso hacia delante, durante los APA's, el CoP se mueve hacia atrás y hacia delante, por ese orden. En cambio, cuando queremos realizar un paso hacia atrás, durante los APA's, el CoP se mueve hacia delante y hacia atrás (sentidos contrarios respecto al paso hacia delante). La superficie disponible en los pies para realizar los APA's durante el paso hacia delante es más pequeña que la disponible cuando realizamos el paso hacia atrás (figura 3.5.5).

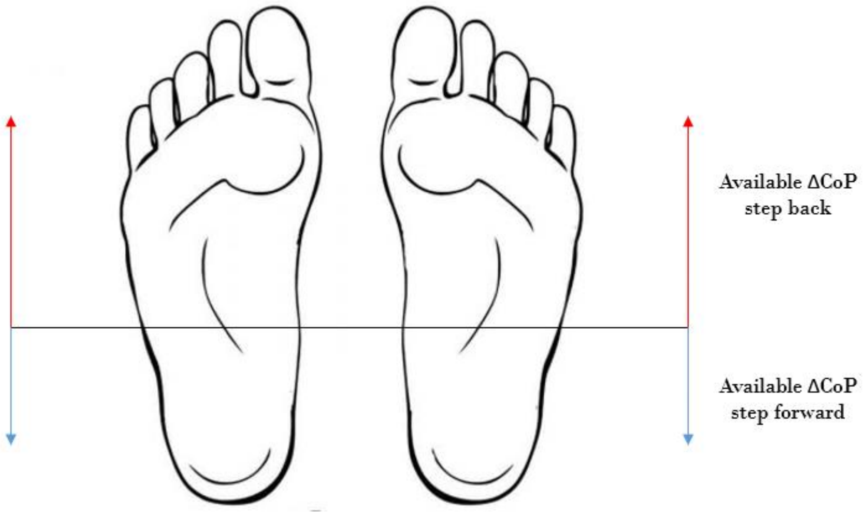

Fig. 3.5.5. Superficie disponible para mover el CoP durante los APA's en los pasos adelante y atrás

ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

SCUOLA DI INGEGNERIA E ARCHITETTURA

CORSO DI LAUREA IN INGEGNERIA ELETTRONICA

TESI DI LAUREA
in
Bioingegneria della Riabilitazione M

A multi-sensor investigation of anticipatory postural adjustments in voluntary movement initiation

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Anno Accademico 2015-16

Sessione I

INDEX

1.- INTRODUCTION

From the time of our birth we are discovering how to move about in the world. We start developing our locomotor skills during our first years and we keep refining them until our adult age. These locomotor skills are the foundation of human movement and include activities as walking, running, skipping, hopping, galloping, leaping, jumping or sliding. During our daily life as adults we are required to perform certain tasks that need a refined coordination and physical ability. Without this physical ability, we are not able to success on the execution of these tasks and therefore we cannot maintain a normal lifestyle. Examples of crucial tasks that we have to deal with every day are walking, step climbing or chair standing.

Due to this importance in our everyday life (among other reasons), the human locomotion function has been an attractive topic for studies over the last several centuries. These studies have depended on the methods available at every time; having a look at the history we can appreciate the evolution of the human movement studies.

1.1.- Brief history of human movement analysis

Everything began with the ancient Greek philosopher Aristotle (−383 to −321) [1]. He published a text on the gait of animals. The text applies basic geometry and mathematics to analyse the movement, explains some experiments (e.g., “If a man were to walk parallel to a wall in sunshine, the line described (by the shadow of his head) would be not straight but zigzag...”) and discusses some interesting questions as “why do man and bird, though both bipeds, have an opposite curvature of the legs?”. It is interesting to highlight that in classical antiquity, motion patterns of humans were usually studied in close relation to motion patterns of animals, as showed on Figure 1.1.1. In addition, the text also includes detailed observations about the motion patterns of humans during different daily tasks. This text is the first known document on biomechanics.

During the renaissance, Leonardo Da Vinci (1452 – 1519) was one of the main actors of the human analysis. He focused a big number of his studies in human anatomy and a smaller part in human motion. He wrote in one of his sketchbooks “ For a man going upstairs (Figure 1.1.2) the centre of mass of a human who is lifting one foot, is always on top of the centre of the sole of foot (on which he is standing). A human going upstairs shifts weight forward and to the upper foot, creating a counter weight against the lower leg, such that the workout of the lower leg is reduced to moving itself. When going upstairs, a human starts with relieving body weight from that foot which he is going to lift. Furthermore, he dislocates the remaining body mass onto the opposite leg, including the (weight of the) other leg. Then he lifts this other leg and places the foot on the step, which he likes to climb on. Next he dislocates the whole body weight, including that of this leg, onto the upper foot, puts his hand onto his thigh, slides his head forward, and moves towards the tip of the upper foot, quickly lifting the heel of the lower foot. With this push he lifts himself upward, simultaneously he straightens the arm which was resting on the knee. This stretching of the arm pushes body and head upward, and thus also straightens the back which was bended before." [1]

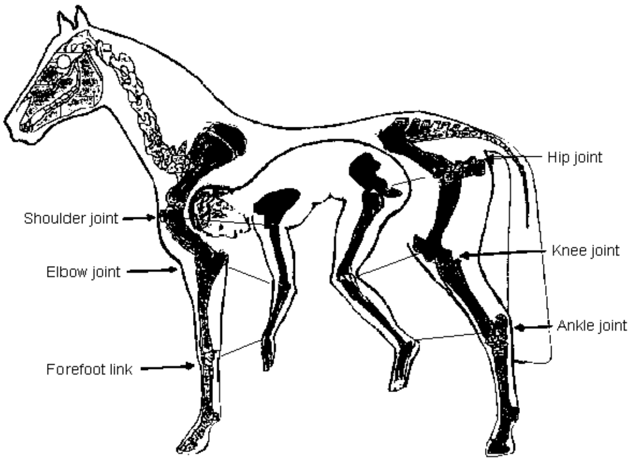


Fig. 1.1.1. Evolutionary relations between joints of humans and horses.

More than 500 years ago he described perfectly (without any instrumentation) the variation of the position of the centre of mass during a daily task as step climbing.

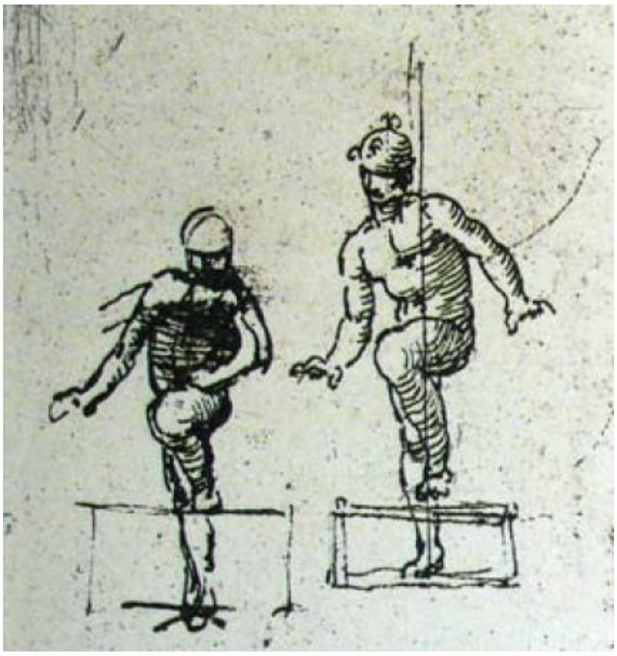


Fig. 1.1.2 Sketch from Leonardo Da Vinci representing a man climbing a step

During the Baroque the most notable scientist in human motion area was Giovanni Alfonso Borelli (1608-1679). He wrote "On the Movement of Animals", where he applied to biology the analytical and geometrical methods in mechanics developed by Galileo Galilei (1564-1642). He was the first to mix in a deep way these two areas of knowledge (mechanics and biology) and to change from visual (qualitative) observation to quantitative measurements. These two new approaches made biomechanics emerge and because of it he is often called "The father of biomechanics". He "was the first to understand that the levers of the musculoskeletal system magnify motion rather than force, so that muscles must produce much larger forces than those resisting the motion" [2]. He realized that bones serve as levers and muscles function according to mathematical principles. The principles he stablished have become a basic for modelling human motion.

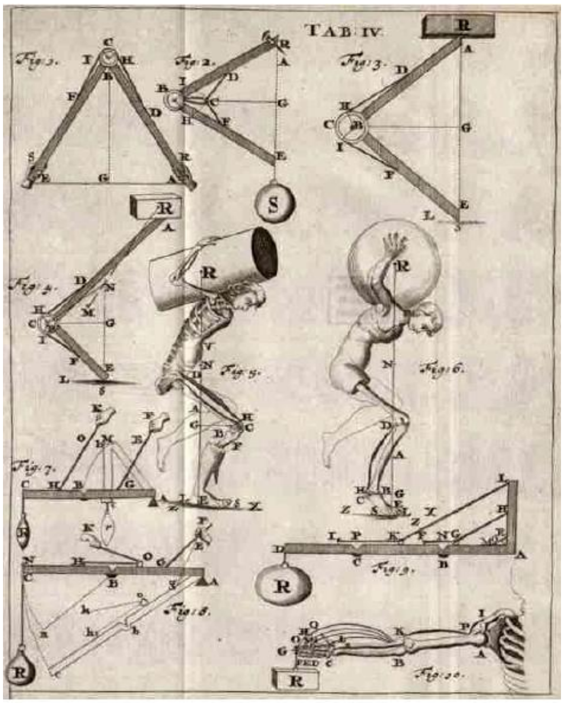


Fig 1.1.3. Designs of Borelli

Later came the Age of Enlightenment, when there were not many relevant contributions to the study of human motion itself. However, during these and the following years, there were other contributions crucial to the future developments and understanding of general mechanics. Isaac Newton (1642-1727) founded modern dynamics including his three laws of motion, and ''created'' the calculus. Some years before Rene Descartes (1596-1650) had basically stablished modern mathematics (geometry and algebra). Over the following years there were improvements in many other science areas as well, such as thermodynamics or electricity.

During the XIX century the appearance of the photo camera opened a new world of possibilities for the study of human movement. The Weber brothers [3], reported one of the first quantitative studies of the temporal and distance parameters during human locomotion. Their work stablished a model for subsequent quantitative studies of human locomotion [4].

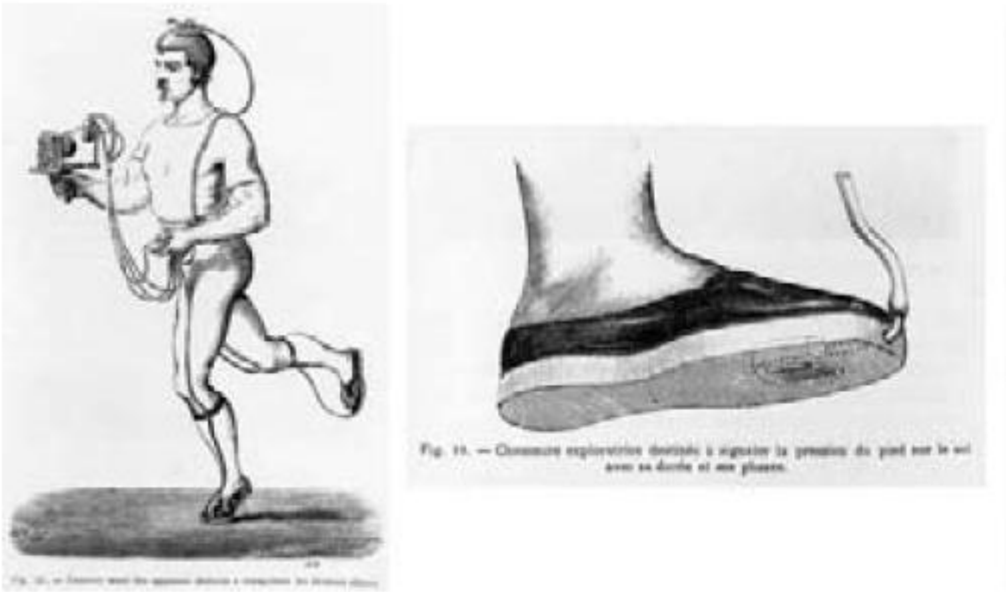


Fig. 1.1.4. A runner with instruments to record his movements, including a shoe to record duration and phases of ground contact [5]

Later that century, the contemporaries Marey (1830-1904) and Muybridge (1830-1904), were among the first to quantify patterns of human movement using photographic techniques [6]. Another two contemporaries of them, the anatomist Wilhelm Braune (1831-1892) and the mathematician Otto Fisher (1861-1917) were the first to report measurements of body segment movements to calculate joint forces and energy expenditures using the classic Newtonian mechanics [7]. The study had a very specific purpose: their work was motivated by military applications related to improving the efficiency of troop movement.

The 1950s was a crucial period for the development of human movement analysis. The need for an improved understanding of locomotion for the treatment of World War II veterans was one of the reasons that made this period so important for the evolution of biomechanics.

In the past years, the improvement of the available instrumentation and the rise of the computer technologies have provided new opportunities for the advancement of the study of human locomotion. These improvements and new available methods have made it feasible to extend the application of kinetic analysis to clinical problems.

Nowadays, some of the most common methods and instruments for human movement analysis are stereophotogrammetry, fluoroscopy, force platforms or body-worn sensors. Every of the mentioned methods and instruments have diverse characteristics and thus are more suitable for different applications.

1.2.- The gait cycle

Even if the main objective of the project was not the gait analysis, it is convenient to understand how the gait cycle works. This is important in order to have a general picture about the context where our study is applied.

The gait cycle is the continuous repetitive pattern of walking or running. It is split into two main phases, stance and swing, with one complete gait cycle including both a stance and swing phase.

The first phase is the stance phase. It is the period where the foot is in contact with the ground and equates to 60% of the cycle when walking. It is divided into other 4 sub-phases:

• Heel strike: The point when the heel hits the floor

• Foot flat: The point where the whole of the foot comes into contact with the floor

• Mid stance: Where we are transferring weight from the back, to the front of our feet

• Toe off - Pushing off with the toes to propel us forwards

The swing phases makes up the remaining 40%. During walking there is a period called double stance, where both feet are in contact with the ground. As the stance phase, it is divided in other different sub-phases:

• Acceleration - The period from toe off to maximum knee flexion in order for the foot to clear the ground

• Mid-swing - The period between maximum knee flexion and the forward movement of the tibia (shin bone) to a vertical position

• Deceleration - The end of the swing phase before heel strike

When running, a higher proportion of the cycle is swing phase as the foot is in contact with the ground for a shorter period. Because of this there is now no double stance phase, and instead there is a point where neither feet are in contact with the ground, this is called the flight phase. As running speed increases, stance phase becomes shorter and shorter [8].

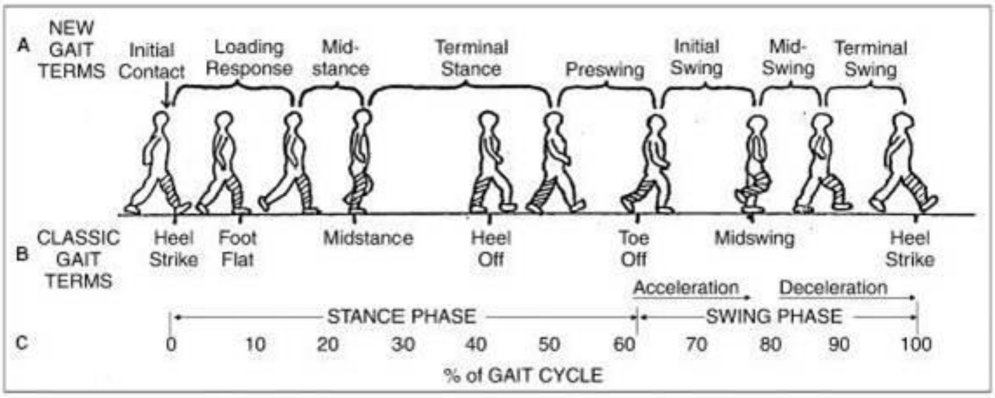


Fig 1.2.1. Phases of the gait cycle

1.3.- Center of mass (CoM) and center of pressure (CoP)

The centre of mass (CoM) and centre of pressure (CoP) concepts will be constantly used in the study, and therefore it is important to define them before.

1.3.1.- Center of mass

The center of mass of a distribution of mass in space is the unique point where the weighted relative position of the distributed mass sums to zero. It is the point where if a force is applied causes it to move in direction of force without rotation. In other words, the concept of the center of mass is that of an average of the masses factored by their distances from a reference point.

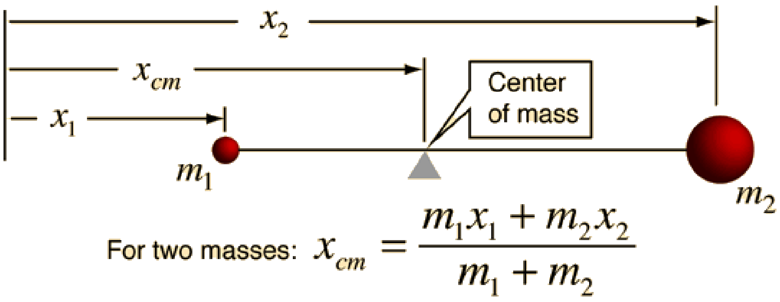


Fig. 1.3.1. Explanation of the center of mass concept [9]

The location of the center of mass of the human body depends on the gender and the position of the limbs. It changes depending on the posture as well, as shown on Figure 1.3.2.

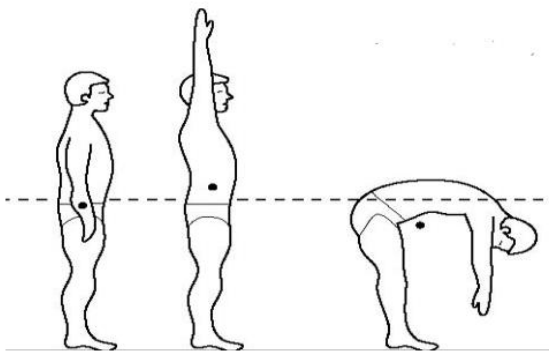


Fig 1.3.2. Location of the CoM for different postures

In a standing posture, it is typically about 10 cm lower than the navel, near the top of the hip bones. It is commonly assumed that it is located where the L5 vertebra is.

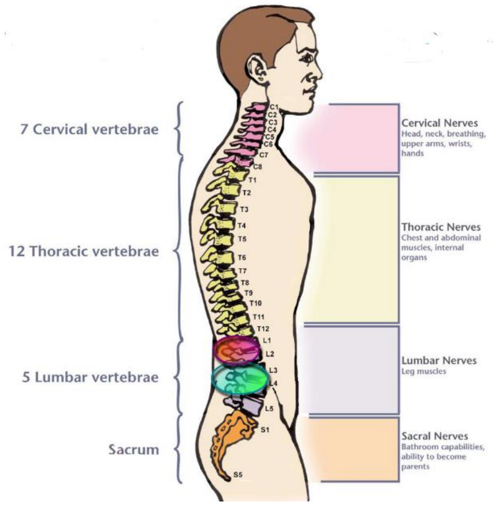


Fig. 1.3.3. Location of the different sets of vertebras in the spine

1.3.2.- Center of Pressure

In biomechanics, the center of pressure (CoP) is the term given to the point of application of the ground reaction force vector. The ground reaction force vector represents the sum of all forces acting between a physical object (the human body) and its supporting surface. The center of pressure is the location on the supporting surface where the resultant vertical force vector would act if it could be considered to have a single point of application. It is thought that changes in motor control may be reflected in changes in the center of pressure.

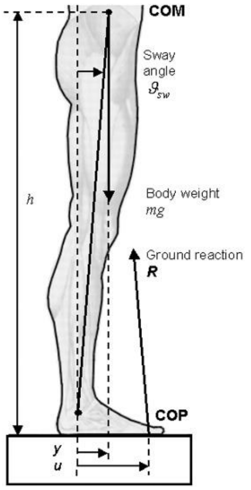


Fig. 1.3.4. CoP in standing position

The center of pressure is not a static outcome measure. The effect of movements' execution will regularly be quantified by alterations in the center of pressure. For instance, during human walking, the center of pressure is near the heel at the time of heelstrike and moves anteriorly throughout the step, being located near the toes at toe-off. For this reason, analysis of the center of pressure needs to take into account the dynamic nature of the signal. The CoP and its displacements are usually measured using a force platform, but they can measured using other devices (in example insole systems).

1.4.- Anticipatory Postural Adjustments (APA's)

Prior to the first step that would yield us to the gait cycle, we should do a transition from a quiet standing posture in double-limb support, to dynamic equilibrium that allows forward body progression [10]. The step initiation process is composed by a preparatory phase and a stepping phase.

During the first phase the anticipatory postural adjustments (APA's) appear. They involve a variation of the position of the centre of mass (CoM) and the centre of pressure (CoP) of our body. For a normal step, the CoP movement follows this pattern: it shifts backward and toward the swing limb, in order to move the body centre of mass forward and over the stance limb, in preparation for single-limb support [11] [12] [13] . The second phase (the stepping phase) starts when the weight has been transferred to the stance limb and thus the swing limb is ready to move forward. As defined in [14] "the beginning of the step is the end of the APA".

However, it is important to highlight that the APA's are present before every kind of voluntary movement, not only before starting to walk. Just to give some examples, they appear before standing on one leg, before negotiating a step or before leaning forward to reach a far object. Depending on the required movement the APA's have different characteristics. They change as well depending on the inclination of the floor [15], posture [16], age [17] [18], the presence of different neurodegenerative diseases such as Parkinson Disease [19] or Huntington's chorea [20], or if the patient has suffered of stroke or amputation [21].

We can define the APA's as the pre-movements of our body (changes of the posture) that take place before the main movement. The purpose of the APA's is to balance our body (by means of changing the position of the CoP and CoM) in order to reach a more suitable dynamic equilibrium for the consecutive movement. These movements are relatively small and cannot be appreciated without the help of adequate instrumentation.

The study of the APA's has increased its importance over the last years since many studies have proved that it is a powerful instrument to detect and evaluate the different stages of several neurodegenerative diseases [22] [23].

From these neurodegenerative diseases, the one whose APA's have been more studied is the Parkinson's disease (PD). It has been shown that the investigation of APA's would be useful to detect PD in early stages, when clinical evidence of start hesitation may not be even detectable [22]. Moreover, there is also some variety of other studies relating APA's and PD: studies comparing patients taking or not levodopa medication [10] or experiments analysing different tasks such as step climbing [23] or regular step initiation [10] [22].

Regarding the different instrumentation and experimental methods used, the classic setup for these studies involves the force platform and, more recently, accelerometers. In some recent studies even smartphones have been used [24]. As mentioned above, the APA's are relatively small movements and thus cannot be properly characterized by video cameras. The advantage of the accelerometers compared to the force platform is its price and portability. The force platform may be a more reliable and accurate sensor, but its price is high compared with the accelerometers and usually requires of a motion analysis lab. In addition, accelerometers can be used everywhere due to their small size and wireless data transfer system. There is no need to have a fully equipped laboratory for using them; just a computer with the adequate software and some space to perform the required movements are required.

2.- PURPOSE

The objective of the study is to analyse the anticipatory postural adjustments (APA's) during different movements required for our daily tasks. We have compared the APA's of 10 different movements starting from 4 different configurations: open eyes/closed legs (OE/CL), open eyes/open legs (OE/OL), closed eyes/closed legs (CE/CL) and closed eyes/open legs (CE/OL).

It is interesting to analyse the effect of the heel distance prior to the movement since it can be appreciated from previous studies, that there is not a fixed standard regarding the distance between heels when studying the APA's. Some of them fix a certain distance [22] [25] whereas others let the subject be in a comfortable position of their choice [23] [26] [27]. Regarding the differences between movements with open and closed eyes, the objective is to see the influence of the different sensory inputs in the APA's.

For the current study we have used a force platform, 2 accelerometers and one pressure insole system. The force platform is a standard for APA's studies and gait analysis. Accelerometers have been used over the last years for APA's analysis, since they are cheap and portable. The insole system has not been commonly used in this kind of studies, and provides different information than the other devices.

Parameters commonly used in these kind of studies (found in the bibliography) were calculated to compare the effect of the 4 different starting configurations.

3.- MATERIALS

As mentioned above, 3 different types of sensors have been used for the study. They will be described in the following sections.

3.1.- Force platform

The force platform is an instrument designed to measure the forces and moments applied to its top surface as a subject performs different movements (stand, step, jump…) on it. It is commonly used in research and clinical studies looking at balance, gait and sports performance. It measures different parameters, such as the Center of Pressure (CoP) or the force exchanged between the body and the floor, the ground reaction force (GRF). From the direct measure of the GRF and using other methods and instrumentation (in example stereophotogrammetry) we can estimate other parameters related to the kinematics of the body.

3.1.1.- Operating principle

The device has 4 load cells placed under the platform that convert the mechanical actions in electrical signals. These load cells can be made of strain gauges or piezoelectric transducers. Depending on the type of load cells used, force platforms have different characteristics. A brief summary of the advantages and disadvantages of both types can be found on Table 3.1.1.

Strain gauges	Piezoelectric
- Less sensibility	+ Sensibility
+ Less cost	- More cost
+ Small effects of ageing	- Drift

Table 3.1.1. Advantages and disadvantages of type of load cells

The high natural frequency of the piezoelectric sensors (among other reasons) make them more suitable for dynamic applications (they are not precise for long-time tests), whereas force platforms equipped with strain gauges are more suitable for longer applications where having and extremely fast response is not that important. The force platform (or force plate) can measure 4 different physical magnitudes:

- Ground reaction force. It is the force exchanged between the body of the subject and the platform. It is expressed in a 3D system and thus decomposed in the 3 orthogonal directions XYZ. The Ground Reaction Force can be calculated with the following procedure (see Figure 3.1.2)

$$GRFx = Fx1 + Fx2 + Fx3 + Fx4$$
$$GRFy = Fy1 + Fy2 + Fy3 + Fy4$$
$$GRFz = Fz1 + Fz2 + Fz3 + Fz4$$

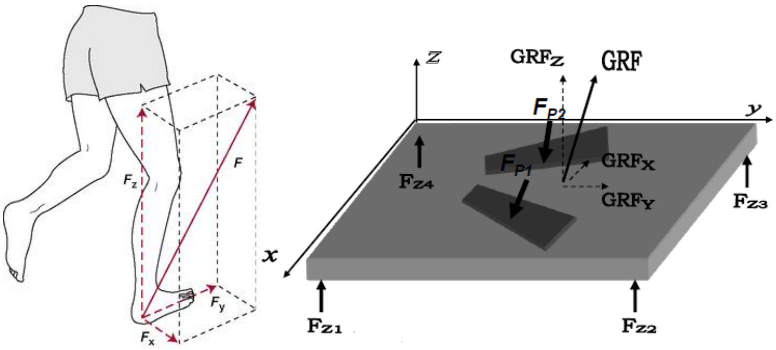


Fig. 3.1.1 and 3.1.2. Decomposition of the GRF and force distribution in the force platform [28]

- The moment of the GRF with respect to a known point (usually the centre of the force platform or one of his angles). It is also expressed in the 3 orthogonal directions XYZ.

$$Mx = (Fz2 + Fz3 - Fz1 - Fz4) \times a$$

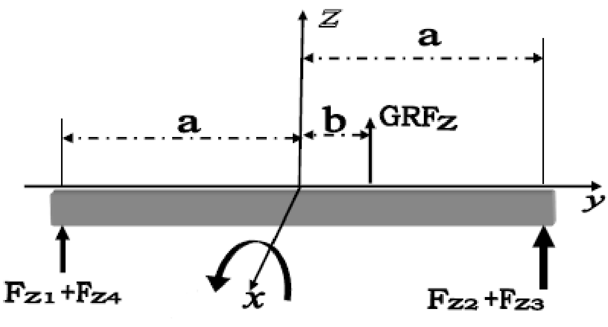


Fig. 3.1.3 Moment of the GRF with respect to the center of the platform [28]

- The Centre of Pressure (CoP). It is defined as the point of application of the GRF. It is expressed by the coordinates X and Y.

$$COPy = \frac{(Fz2 + Fz3 - Fz1 - Fz4) \times a}{Fz1 + Fz2 + Fz3 + Fz4}$$

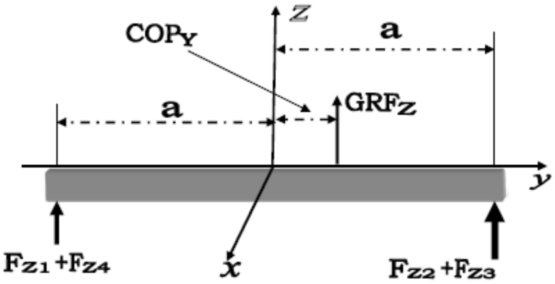


Fig. 3.1.4 CoPy in the force platform [28]

- The free vertical moment (Z axis) that indicates the twist of the foot on the platform. In other words, it is the torque applied by the foot.

$$Mt = Mz - GRFy \times COPx + GRFx \times COPy$$

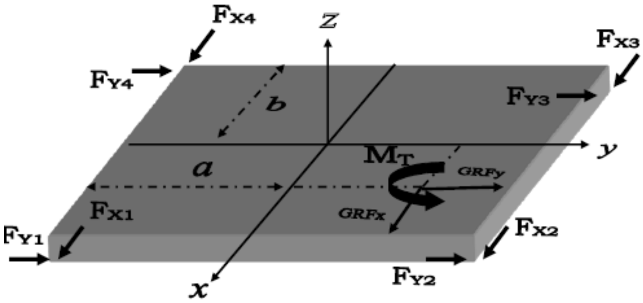


Fig. 3.1.5 Vertical free moment on the force platform [28]

3.1.2.- Used force platform: Bertec legacy balance plate

The Bertec legacy balance plate is a simple, light and easy to set-up force plate. It has an adjustable foot to counteract uneven surfaces, and markers on the top surface for foot alignment. The force platform is connected to the computer through an USB cable. The sampling frequency of the device is 1000 Hz and it uses his own software.

Fig. 3.1.6. Bertec legacy balance plate

3.2.- Accelerometers

Accelerometers are inertial sensors that measure the acceleration in three orthogonal axes. They have many applications; they are commonly used as an inertial measurement of velocity and position, as a sensor of inclination or orientation in 2 or 3 dimensions (as referenced from the acceleration of gravity) or as a vibration or impact (shock) sensor.

3.2.1.- Operating principle

Most accelerometers are Micro-Electro-Mechanical Sensors (MEMS). The basic principle of operation behind the MEMS accelerometer is the displacement of a small proof mass etched into the silicon surface of the integrated circuit and suspended by small beams. Consistent with Newton's second law of motion (F = ma), as an acceleration is applied to the device, a force develops which displaces the mass. The support beams act as a spring, and the fluid (usually air) trapped inside the IC acts as a damper, resulting in a second order lumped physical system. This is the source of the limited operational bandwidth and non-uniform frequency response of accelerometers.

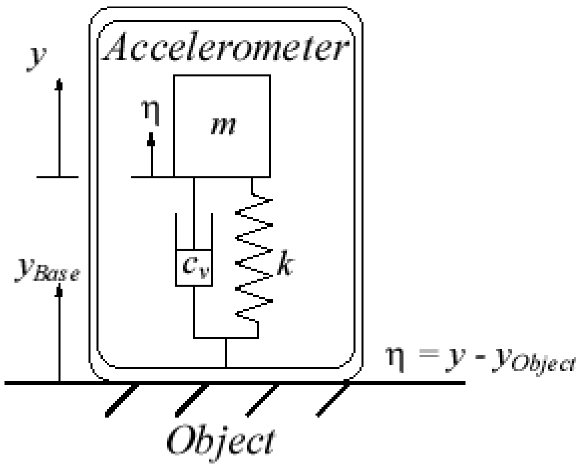


Fig. 3.2.1. Accelerometer diagram

3.2.2.- Types of accelerometers

The classification of the accelerometer depends on the principle upon which it can be built. Two very common types utilize capacitive sensing and the piezoelectric effect to sense the displacement of the proof mass proportional to the applied acceleration.

- Capacitive. Accelerometers that implement capacitive sensing output a voltage dependent on the distance between two planar surfaces. One or both of these “plates” are charged with an electrical current. Changing the gap between the plates changes the electrical capacity of the system, which can be measured as a voltage output. This method of sensing is known for its high accuracy and stability. Capacitive accelerometers are also less prone to noise and variation with temperature, typically dissipate less power, and can have larger bandwidths due to internal feedback circuitry.

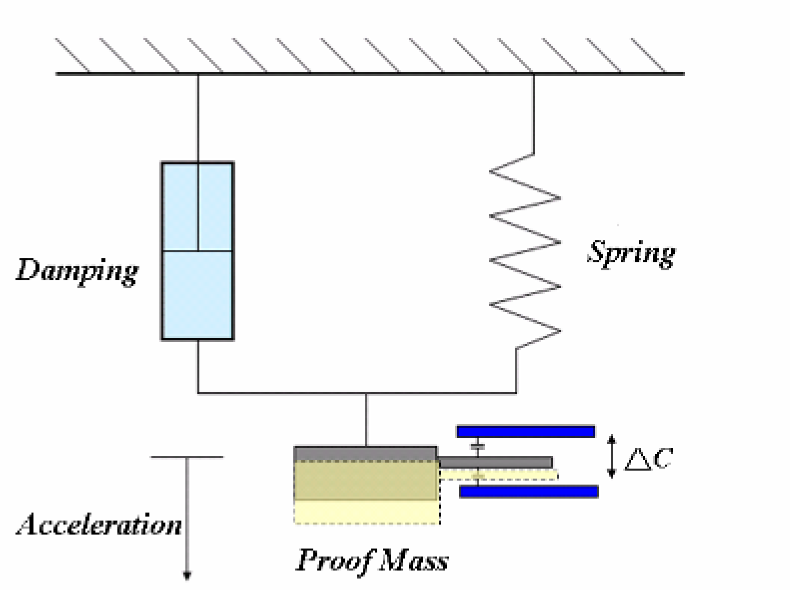


Fig. 3.2.2. Capacitive accelerometer diagram

- Piezoelectric. Piezoelectric sensing of acceleration is natural, as acceleration is directly proportional to force. When certain types of crystal are compressed, charges of opposite polarity accumulate on opposite sides of the crystal. This is known as the piezoelectric effect. The charge accumulates on the crystal and is translated and amplified into either an output current or voltage. Piezoelectric accelerometers only respond to AC phenomenon such as vibration or shock. They have a wide dynamic range, but can be expensive depending on their quality.

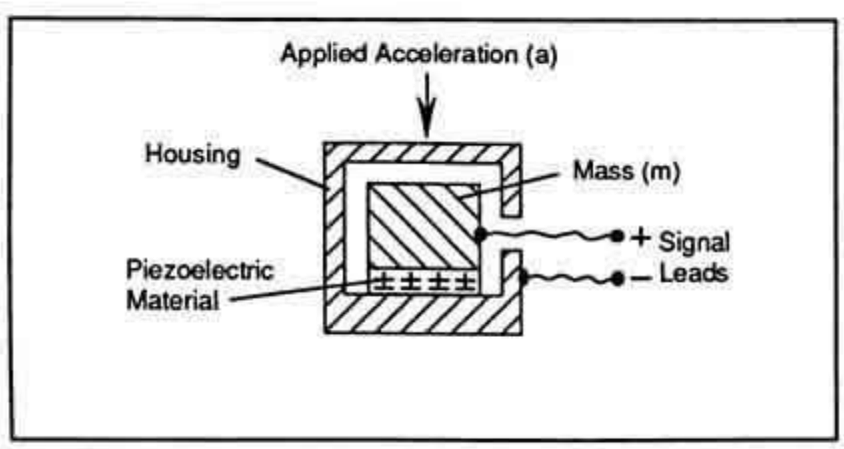


Fig. 3.2.3. Piezoelectric accelerometer diagram

3.2.3.- Used accelerometers: EXLs3

The EXLs3 accelerometer is composed of a tri-axial accelerometer, gyroscope and compass, a 32-bit Cortex microprocessor for data processing and a Bluetooth radio to send real-time data. For the study only the data obtained by the accelerometer were taken into account.

The Bluetooth system allows to connect the device to a computer as a maximum distance of 10 meter. In addition, it has a 1GB flash drive that makes possible to make an offline treatment of the data via USB. However, for this study the data acquisition has been done online using the Bluetooth system. The on board 32-bit CPU provide algorithms for orientation estimation with Kalman filtering. The devices have a rechargeable Lithium battery that allows streaming up to 3 hours and can be recharged by means of a dedicated docking station.

It has a selectable full-scale range (±2 / ±4 / ±8 / ±16 g) for the a3-axis accelerometer. In the study a full-scale range of ±2 g was used since no greater accelerations will be involved in the proposed movements. Using this smaller full-scale range a bigger precision was achieved.

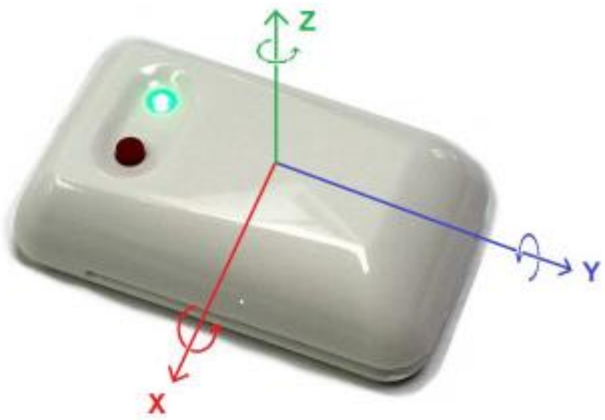


Fig. 3.2.4. Sensing axes of the accelerometer

The possible sampling rates are up to 200 Hz for raw data and 100 Hz for orientation data. In the study a 100 Hz sample rate was used. The EXLs3 accelerometers use a customized software on windows.

3.3.- The Pedar system

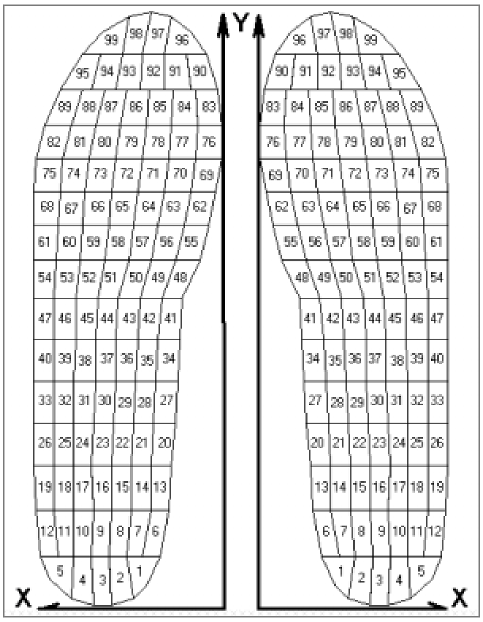
The Pedar®-x is a measurement system for monitoring local loads between the foot and the shoe. The main advantage that it has compared to other sensors and instrumentation (as an example the force platform) is its portability. It can be used without any cable attached to the computer, and the system can last working using one battery for several hours. This makes it suitable for applications and studies when being close to a computer is not possible and requires autonomy. In addition, the system measures separately the magnitudes of pressures exerted by both feet. Comparing with the force platform, the last one just gives us information of both feet at the same time (in example the total ground reaction force or the total CoP). Its repeatability and validity have been proved in several studies [29] [30] [31] [32]. The main disadvantage of the device is its high cost. In addition, even if it is portable it is not really comfortable to wear, due to the weight of the CPU and the number of straps required for its fixation.

Fig. 3.3.1 Pedar system components

LETTER	COMPONENT	LETTER	COMPONENT
A	Insoles	H	Battery cable
B	Double insole cable	I	Battery charger
C	Box	K	Bluetooth dongle
D	Fiber optic cable	J	Start/stop trigger
E	USB cable	L	Velcro straps
F	novel belt	M	SD card
G	pedar-x battery		

Table 3.3.1 Pedar system components

From all the parts that compose the device (showed and described on Figure 3.3.1 and Table 3.3.1) the 2 most important are the portable CPU and the 2 insoles. The insoles are placed between the foot and the shoe. For obtaining reliable measures it is important to use appropriate sport shoes. Every insole is divided on 99 cells, and each of these cells contains capacitive sensors. The sensors measure the force applied by the foot on every cell. There are different sized insoles in order to adapt to different feet sizes.



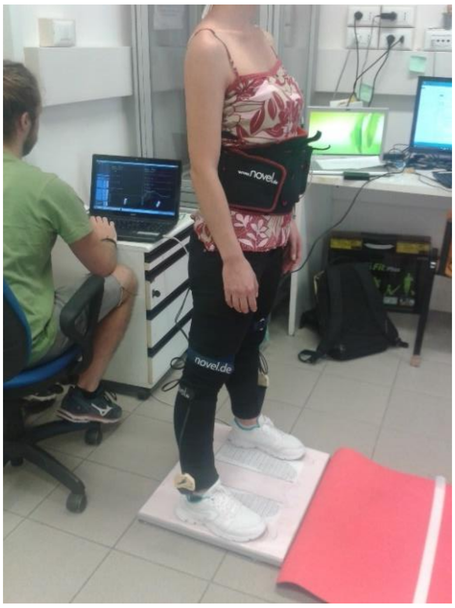


Fig 3.3.2 and 3.3.3. Insole cells and Pedar system fixed on a participant

From the direct force measurements of the sensors, the software calculates other parameters such as the pressure of each cell, the contact area, the peak pressure, the mean pressure, the pressure-time integral value for a selected time period or the force-time integral value for the a selected time period.

The maximum sampling frequency is 20000 sensors per second. This means that when the two insoles are recording data the maximum sampling frequency is 101 Hz (usually 100 Hz is used). In case we are using just one of the insoles, we could set a sampling frequency up to 200 Hz. For our study a sampling frequency of 100 Hz has been used.

Regarding the data acquisition/storing system, the device has 3 different options.

- Bluetooth. Using the Bluetooth system the information can be transmitted online to the computer, when the measurement is taking place.
- Straight connection to the PC. This method is less used since the system loses its main advantage, the portability.
- Using an SD card to store the data. We save the data in a SD card located in the portable CPU and after we can save and look at the data offline in the computer. This last method was the one used in the study.

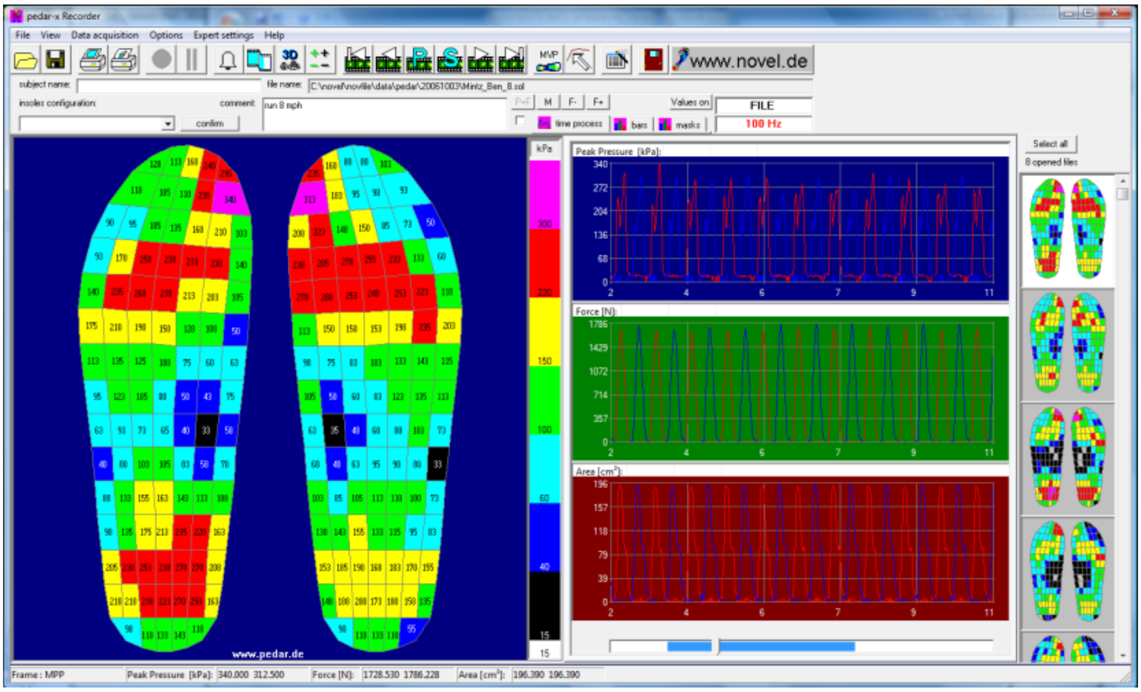


Fig. 3.3.4. Pedar software interface

4.- METHODS

4.1.- Participants

Three healthy subjects voluntarily participated in the study. Ages of participants were in a 24 to 30 years range. Heights were in a 1.65 to 1.77 meters range.

4.2.- Experimental equipment

The participants wore 2 accelerometers EXLs3. The measures of both accelerometers were sampled at 100 Hz and transmitted to a remote PC through a Bluetooth wireless system for the posterior offline analysis. A full-scale range of ±2 g was used in order to make the most of the resolution of the device for this application. Only the information obtained by the accelerometers was used. Data obtained by the gyroscope and compass were not used.

One of the accelerometers was placed on the posterior trunk, close to the L5 vertebra using the belt of the Pedar system. This location for the accelerometer was used in similar studies [22] [25] [33] [34] [35] because it is close to the centre of mass of the body.

The second accelerometer was placed in the area of the C7 vertebra using adhesive tape. This location was also chosen taking into account other studies [22]. However, as said in [1], due to the unpredictable motion of the head during the experiment, measures obtained in this accelerometer are not 100% reliable and should be taken into account very carefully.

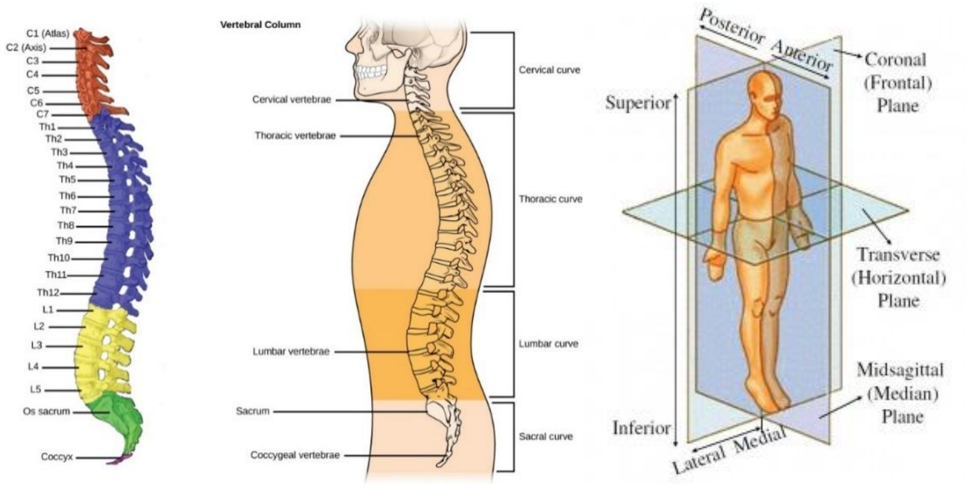


Fig. 4.2.1 and 4.2.2. Location of the vertebras L5 and C7 and body planes and directions

The sensing axes of both accelerometers were parallel. The X, Y and Z axis were oriented along the body medio-lateral (ML), vertical and antero-posterior (AP) directions respectively.

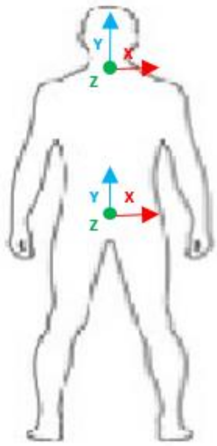


Fig. 4.2.3. Sensing axes of the accelerometers

A force platform Bertec legacy balance plate was used to measure the ground reaction force and the displacement of the CoP. It was connected via USB to the computer of the laboratory. A sampling frequency of 1 kHz was used. Since a sampling frequency of 100 Hz was used for other devices, the data obtained with the platform was re-sampled offline. The force platform had some visual signs in order to help the subjects to place their feet in the required position.

The Pedar system was used to measure different parameters of the feet of the subject. A sampling frequency of 100 Hz was used (the same as the accelerometer). The device was fixed using its different accessories. As a small summary of how to fix the device to the body, the portable CPU was placed on the Pedar belt and the insoles were located between the sport shoes and the socks of the subject. The data was stored in the SD card inserted on the portable CPU for the posterior offline analysis.

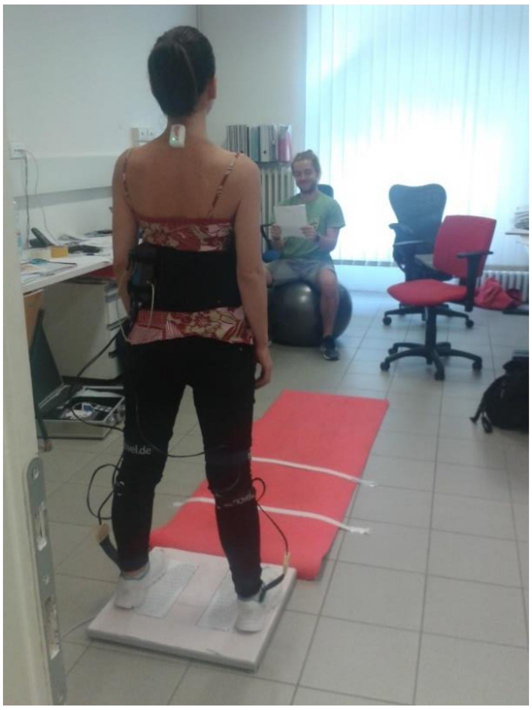


Fig. 4.2.4. Experimental setup

4.3.- Experimental protocol

The experimental procedure was divided in two different parts. The first one was done with the only purpose of synchronize the signals of the 4 different sensors. During the second one the subject was asked to complete the programmed movements.

4.3.1.- Synchronization

The need of synchronization appears due to the impossibility to initiate the data acquisition of the 4 devices at exactly the same time. Initiate the recording of the force platform requires to use its software interface and the accelerometers require to use their own software as well. In addition, the Pedar system uses a remote controller to start the recording. Because of this impossibility to start the data acquisition simultaneously a routine was defined that allowed to have all data obtained by the 4 devices synchronized.

First of all, the software of the 3 types of sensors were switched on in the laboratory computer. The Pedar system and the force platform were calibrated after this first step. Later, the right Pedar insole was placed on top of the force platform. Then the 2 accelerometers were placed on top of the insole. Once all the devices were on top of each other, the data acquisition of the 3 systems started using the computer and the remote control of the Pedar: first the accelerometers, later the force platform and finally the Pedar system.

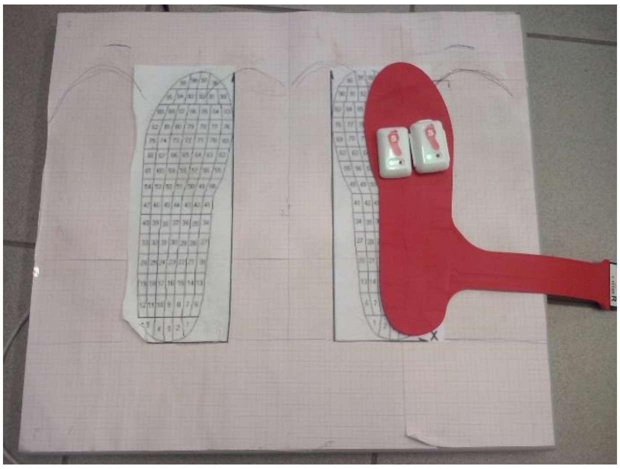


Fig. 4.3.1. Layout before knocking the devices

When all the devices were recording and were placed on top of each other, they were knocked shortly. The objective of this knock was to have a peak on the signals of the 4 sensors that would allow to synchronize them later on using a specially designed Matlab code.

4.3.2.- Movements

The subjects were required to do 10 different movements in order to analyse their APA’s. The movements and their order are described in the Table 4.3.1.

Number	Movement
1	Short step starting with the right leg
2	Long step starting with the right leg
3	Short step starting with the left leg
4	Long step starting with the left leg
5	Step back starting with the right leg
6	Step back starting with the left leg
7	Standing on the left leg
8	Standing on the right leg
9	Turning step to the right
10	Turning step to the left

Table 4.3.1. Order and description of the movements of the experiment

Before starting the full test, the subjects did a short and a long step in order to have an indicator of how long both steps during the full test should be. Two straps were placed at the distance of both steps with the purpose of improving the repeatability, giving the subjects visual information about the approximated desired length of their movements.

Fig. 4.3.2. Straps placed at the short and long step distances

In addition, they were asked to complete the 10 movements with 4 different initial configurations. The order of these configurations was open eyes/closed legs (OE/CL), open eyes/open legs (OE/OL), closed eyes/closed legs (CE/CL) and closed eyes/open legs (CE/OL). This order is summarized in the table 4.3.2. The distance between heels in the closed position was ideally 0 and in the open position 30 cm. Visual signs placed on the force platform helped the participants to place their feet in the required position.

	Open eyes (OE)	**Closed eyes (CE)**
Closed legs (CL)	1st	3rd
Open legs (OL)	2nd	4rd

Table 4.3.2. Order of the initial configurations

The 10 movements starting from 4 different positons make a total number of 40 movements for each test. The total time of every test was around 15 minutes.

Before every movement, the subject was required to stay on the force platform with the pertinent configuration, his arms laying on their sides and looking at the front. They were asked to count up to 5 (approximately 5 seconds). The wait before the movement was required in order to stabilize the body (and thus the CoP) and be able to appreciate better the APA's.

After this 5 seconds wait the participants received a vocal command from the experimenter, indicating the movement they were required to do. After finishing each movement, they were required to come back again to the force platform and keep going with the rest of the movements following the same procedure.

4.4.- DATA ANALYSIS

Since each of the 3 types of sensor used different software, we extracted the data from each of them to text documents. They were later imported to Matlab.

The sample frequency of the force plate was 1 kHz so it was resampled to a frequency of 100 Hz, the same used for the other 3 devices.

Due to some Bluetooth interferences, some data packets from the accelerometers were lost. A Matlab code was created and used to interpolate the data corresponding to this missing packages.

The synchronization was made using a specially defined Matlab code as well. The code had into account the number of the sample corresponding to the moment when the peak (caused by knocking the sensor) appeared on each one of the 4 devices. Using this time information, the signals of the accelerometers and the force platform were shifted. The only signal that remained the same long as the original one was the Pedar signal.

The beginning of the APA's of the 40 movements was identified using the method used in [22] [23] [24]. The standard deviation of the CoP in the medio-lateral direction during the stable phase before each movement was calculated. A threshold value equal to 2 times this standard deviation for each movement was fixed. When the CoP medio-lateral displacement reached this threshold value, that meant that the APA's had started. All the APA's start moments were checked visually. The end of each APA's was defined as the moment when the CoP returned to its pre-movement value.

Different parameters used in the bibliography were calculated and will be shown and discussed in the results and conclusions parts.

5.- RESULTS

In the following sections some abbreviations will be used. These abbreviations are explained in Table 5.1.

Configuration	Abbreviation
Open eyes	OE
Closed eyes	CE
Open legs	OL
Closed legs	CL
Subject i	Si
Movement i	Mi
Time to peak	TTP
Medio-lateral	M-L
Antero-posterior	A-P

Table 5.1 Used abbreviations

The results of every movement are divided in 5 sections.

- *Standard deviation.*
  The medio-lateral CoP standard deviation during the 5 seconds waiting phase prior to the step initiation was calculated. It was calculated in order to fix the threshold value that defined the beginning of the APA's. The threshold value for every subject and movement was fixed as twice the standard deviation of the waiting phase. Figures in this section show the average (of the 3 subjects) standard deviation during the phase prior to the step initiation, sorted by initial configuration.
- *Time to peak.*
  The time to peak was defined as the time difference between the instant of the maximum medio-lateral CoP displacement and the instant of the APA's initiation. Figures on this section show the average (of the 3 subjects) time to peak, sorted by initial configuration.
- *Force and pressure.*
  The first figure shows the evolution of the forces on the feet for a representative subject during a time period from 200 cs before the APA's to 50 cs after the APA's.
  The second figure shows the averaged (of 2 subjects) peak force variation, sorted by initial configuration. The average was done taking into account just the 2 out of the 3 participants since the Pedar results showed abnormalities in the

data of the last subject. The peak force variation was defined as the absolute value of the difference between the force at the beginning of the APA's and the maximum or minimum force (depending on the movement and which one is the swing leg) during the APA's.
The third figure shows the pressure distribution on the feet at the moment of the medio-lateral CoP displacement peak for a representative subject. Up left is shown the picture of the OE/CL configuration, up right of the OE/OL configuration, down left the CE/CL configuration and down left the CE/OL configuration. The positions are summarized in Table 5.2. Figures were extracted from the Pedar software.

OE/CL	OE/OL
CE/CL	CE/OL

Fig. 5.2. Positions of the Pedar figure

- *Acceleration and CoP displacement in the medio-lateral (M-L) direction*.
  The first figure shows the evolution of the accelerations (of both accelerometers) and CoP displacement in the M-L direction, for a representative subject during a time period from 200 cs before the APA's to 50 cs after the APA's.
  The second figure shows the averaged (of the 3 subjects) peak M-L acceleration variation, sorted by initial configuration. This peak M-L acceleration variation was defined as the absolute value of the difference between the M-L acceleration at the beginning of the APA's and the maximum or minimum M-L acceleration (depending on the movement and which one is the swing leg) during the APA's.
  The third figure shows the averaged (of the 3 subjects) peak M-L CoP displacement, sorted by initial configuration. This peak M-L CoP displacement was defined as the absolute value of the difference between the M-L CoP at the beginning of the APA's and the maximum or minimum M-L CoP (depending on the movement and which one is the swing leg) during the APA's.
- *Acceleration and CoP displacement in the antero-posterior (A-P) direction.*
  The first figure shows the evolution of the accelerations (of both accelerometers) and CoP displacement in the A-P direction, for a representative subject during a time period from 200 cs before the APA's to 50 cs after the APA's.
  The second figure shows the averaged (of the 3 subjects) peak A-P acceleration variation, sorted by initial configuration. This peak A-P acceleration variation was defined as the absolute value of the difference between the A-P acceleration at the beginning of the APA's and the maximum or minimum A-P acceleration (depending on the movement and which one is the swing leg) during the APA's.
  The third figure shows the averaged (of the 3 subjects) peak A-P CoP displacement, sorted by initial configuration. This peak A-P CoP displacement was defined as the absolute value of the difference between the A-P CoP at the beginning of the APA's and the maximum or minimum A-P CoP (depending on the movement and which one is the swing leg) during the APA's.

5.1.- Short step starting with the right leg (M1)

5.1.1.- Standard deviation

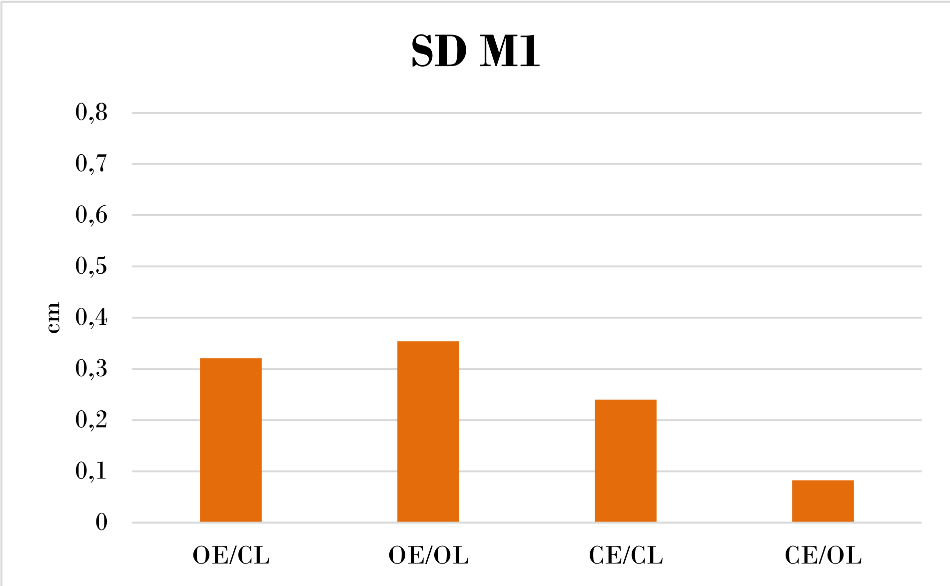


Fig. 5.1.1. Average standard deviation sorted by initial configuration

5.1.2.- Time to peak

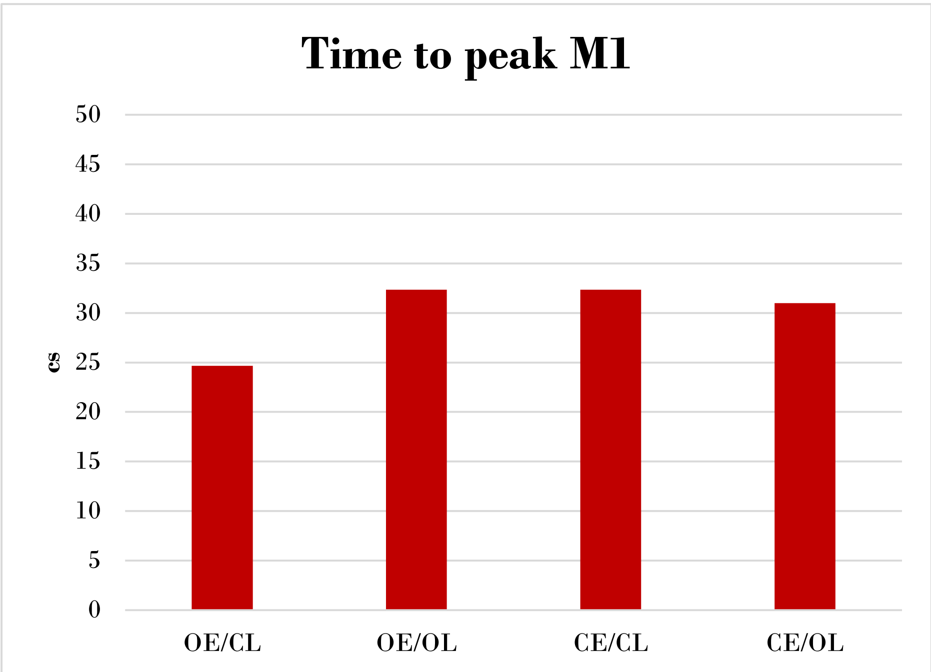


Fig. 5.1.2 Average time to peak sorted by initial configuration

5.1.3.- Force and pressure

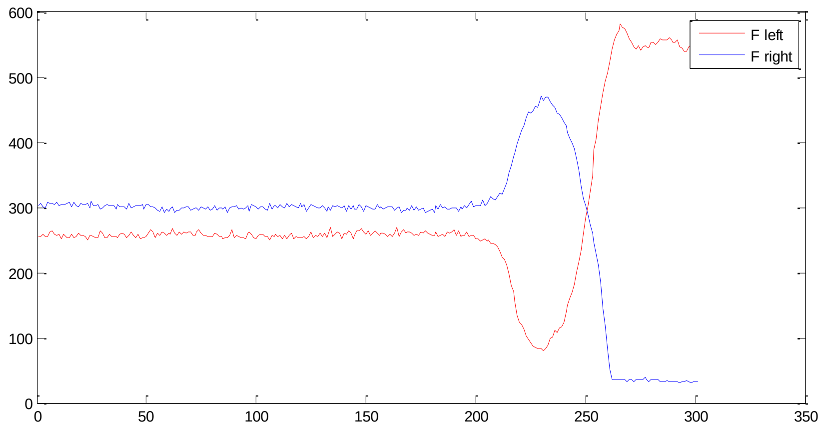


Fig. 5.1.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

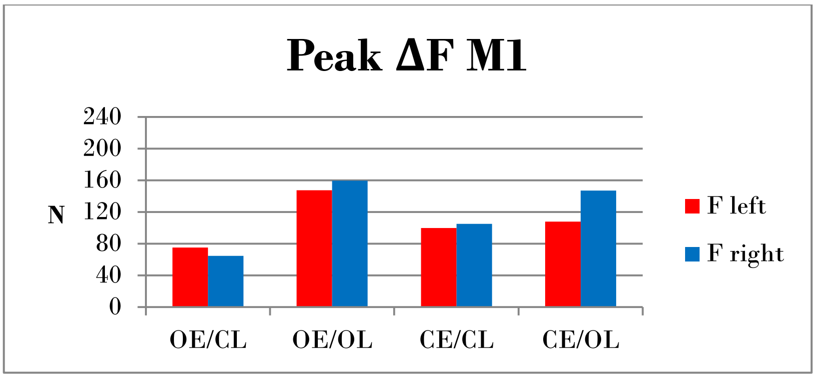


Fig. 5.1.4. Average peak force variation sorted by initial configuration

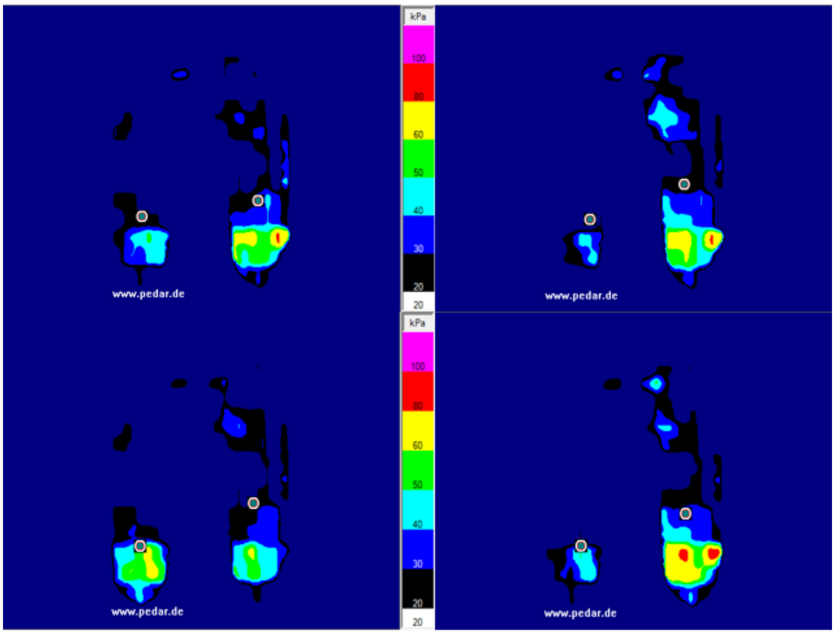


Fig. 5.1.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.1.4.- Acceleration and CoP displacement in the medio-lateral direction

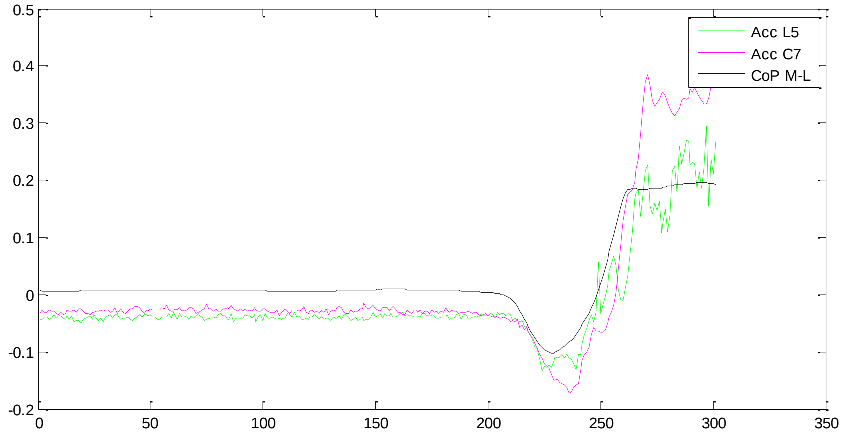


Fig. 5.1.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

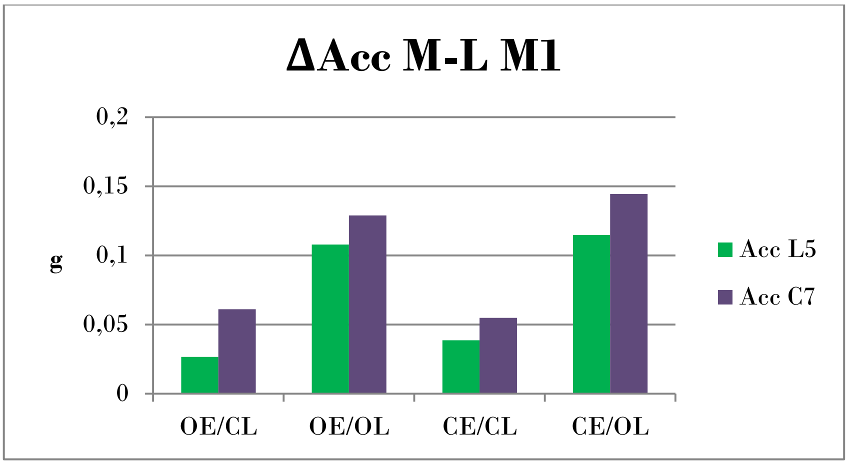


Fig. 5.1.7. Average M-L acceleration variation sorted by initial configuration

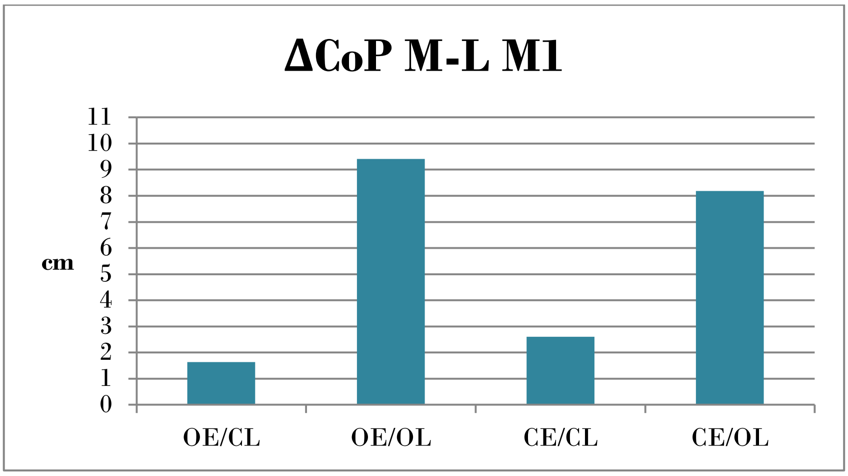


Fig.5.1.8. Average M-L CoP displacement sorted by initial configuration

5.1.5.- Acceleration and CoP displacement in the antero-posterior direction

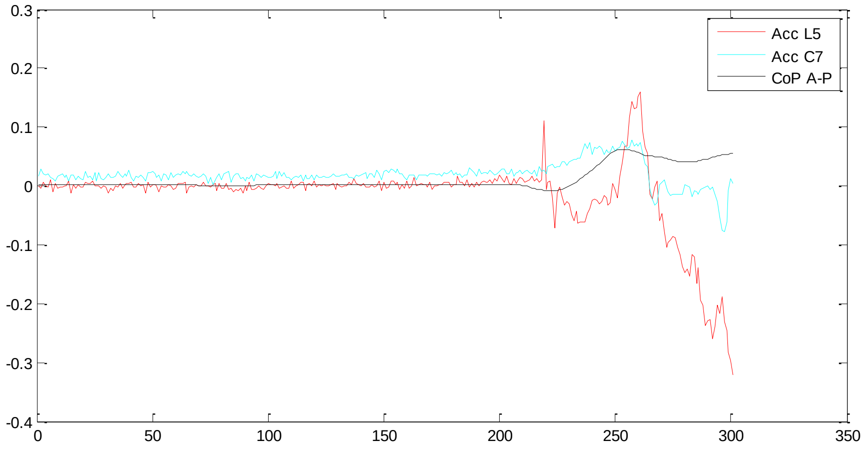


Fig. 5.1.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

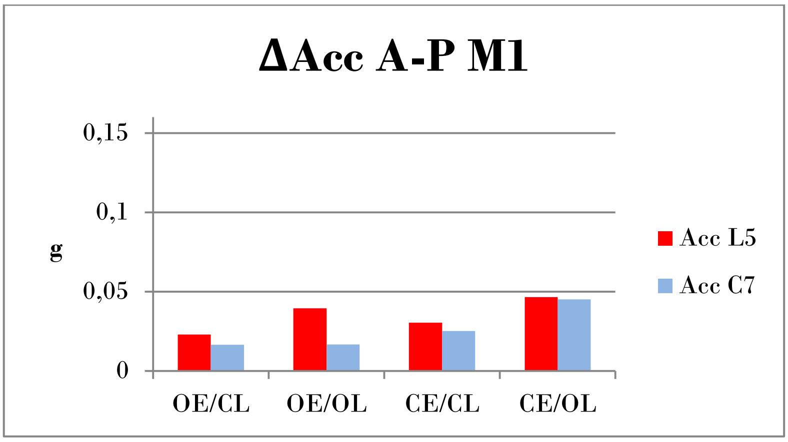


Fig 5.1.10. Average A-P peak acceleration variation sorted by initial configuration

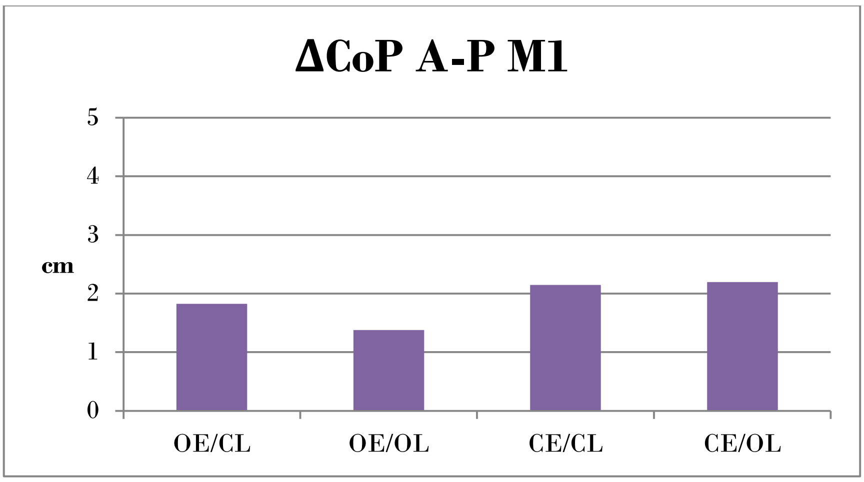


Fig. 5.1.11. Average peak A-P CoP displacement sorted by initial configuratio

5.2.- Long step starting with the right leg (M2)

5.2.1.- Standard deviation

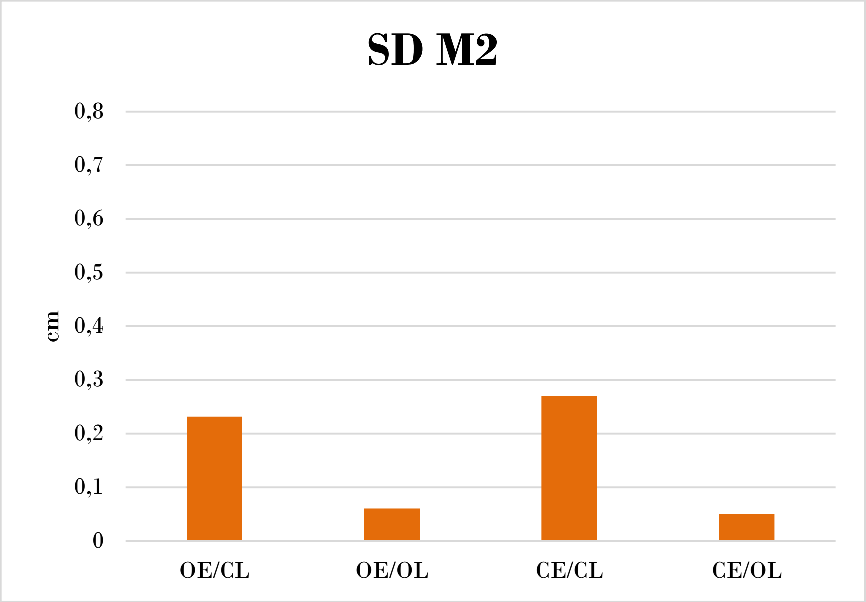


Fig. 5.2.1. Average standard deviation sorted by initial configuration

5.2.2.- Time to peak

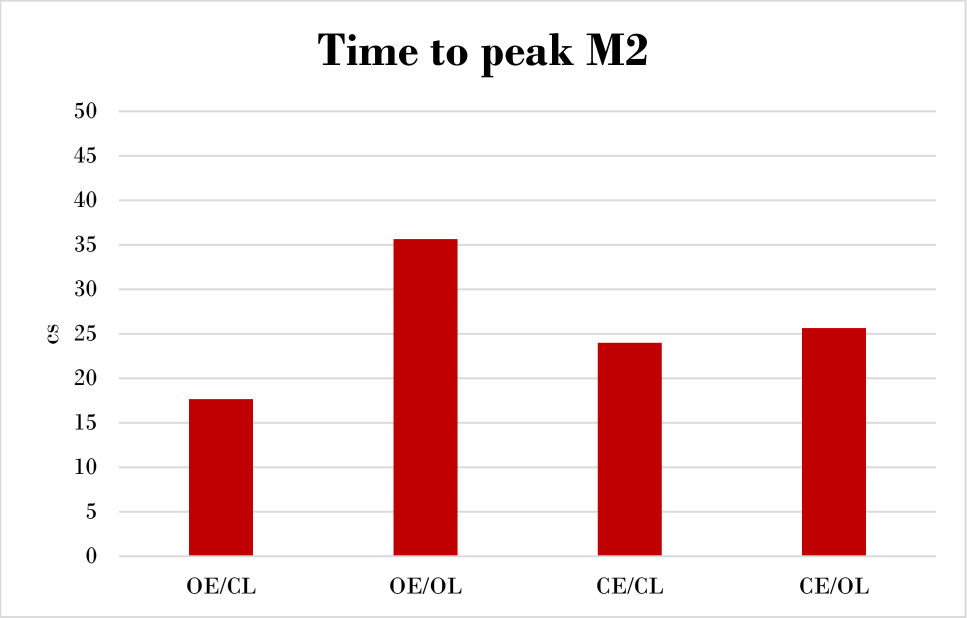


Fig. 5.2.2. Average time to peak sorted by initial configuration

5.2.3.- Force and pressure

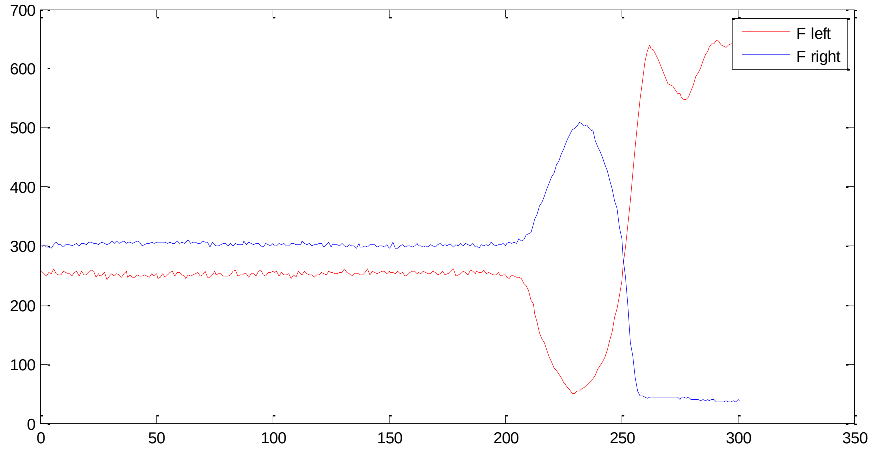


Fig. 5.2.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

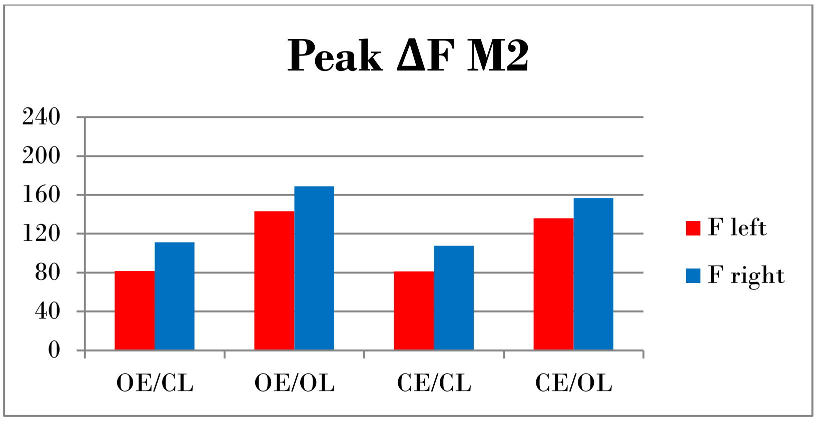


Fig. 5.2.4. Average peak force variation sorted by initial configuration

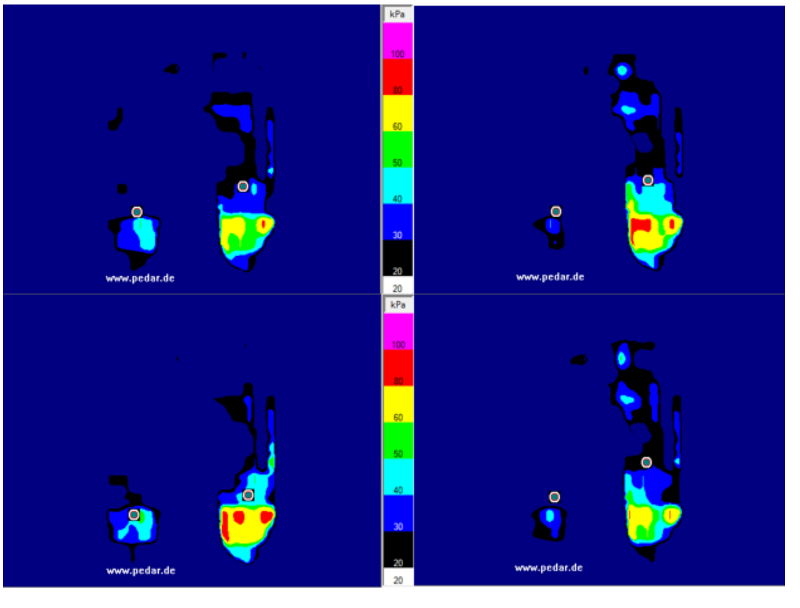


Fig. 5.2.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.2.4.- Acceleration and CoP displacement in the medio-lateral direction

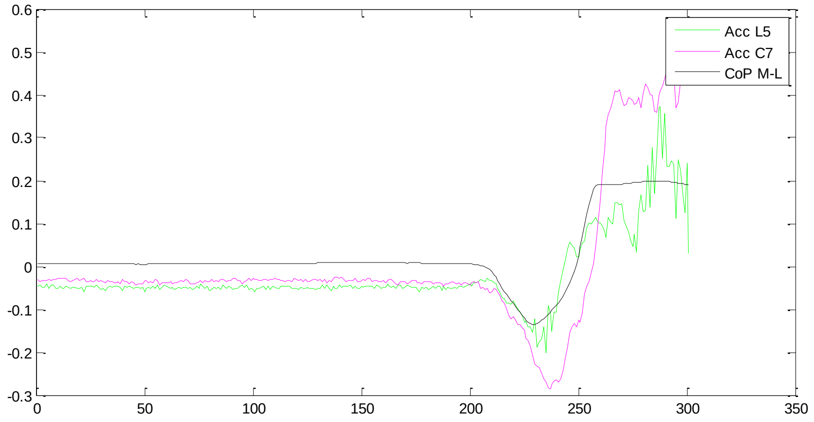


Fig. 5.2.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

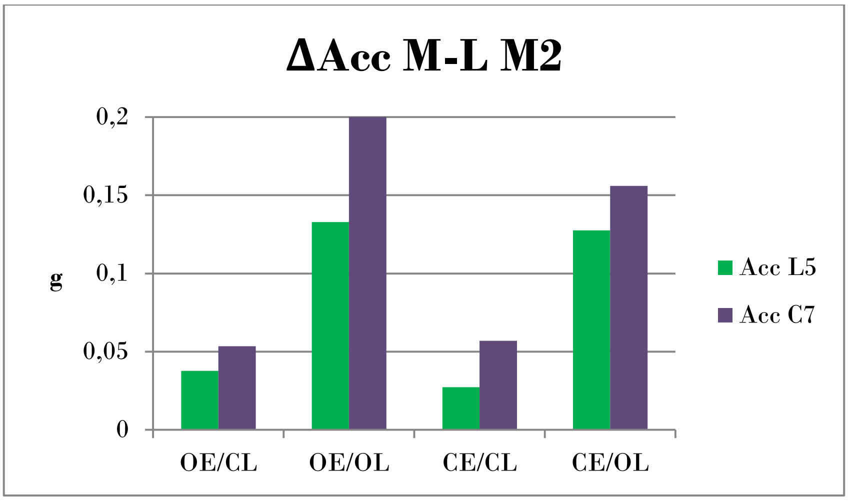


Fig. 5.2.7. Average M-L acceleration variation sorted by initial configuration

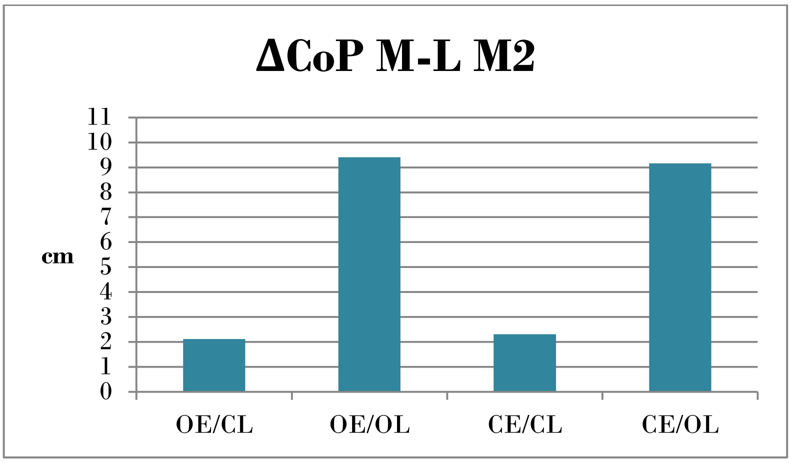


Fig. 5.2.8. Average M-L CoP displacement sorted by initial configuration

5.2.5.- Acceleration and CoP displacement in the antero-posterior direction

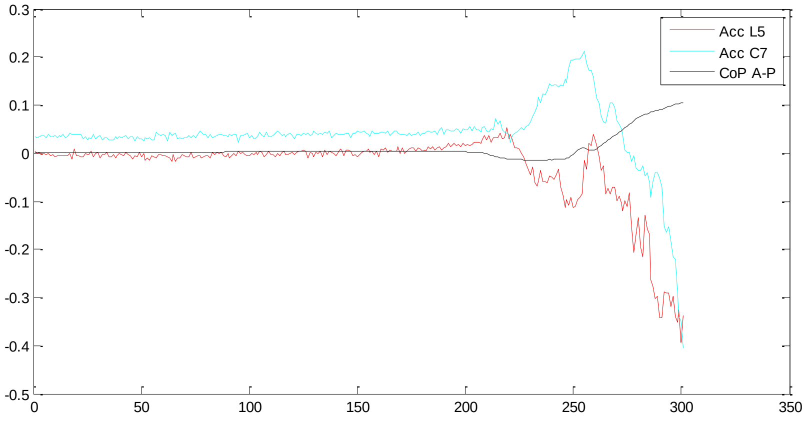


Fig. 5.2.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

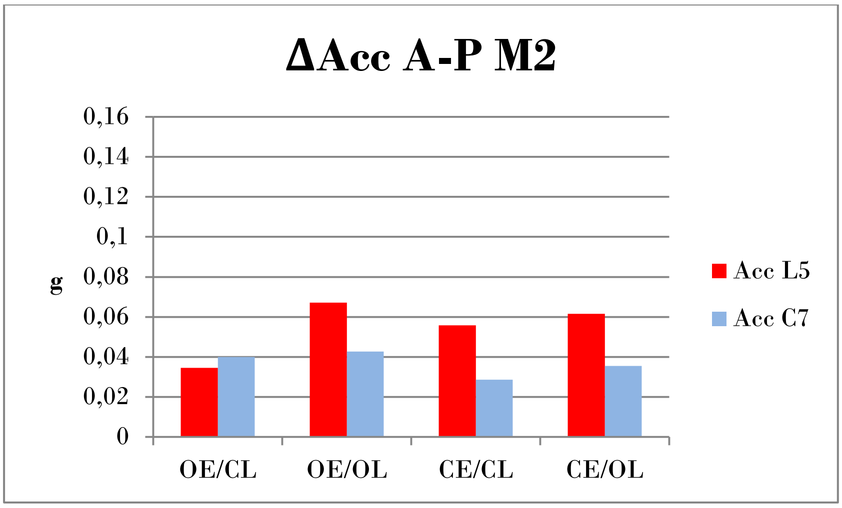


Fig. 5.2.10. Average A-P peak acceleration variation sorted by initial configuration

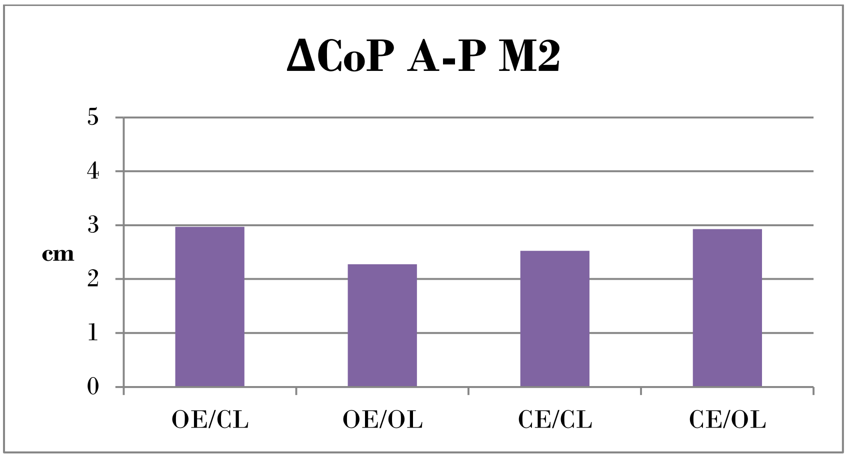


Fig. 5.2.11. Average peak A-P CoP displacement sorted by initial configuratio

5.3.- Short step starting with the left leg (M3)

5.3.1.- Standard deviation

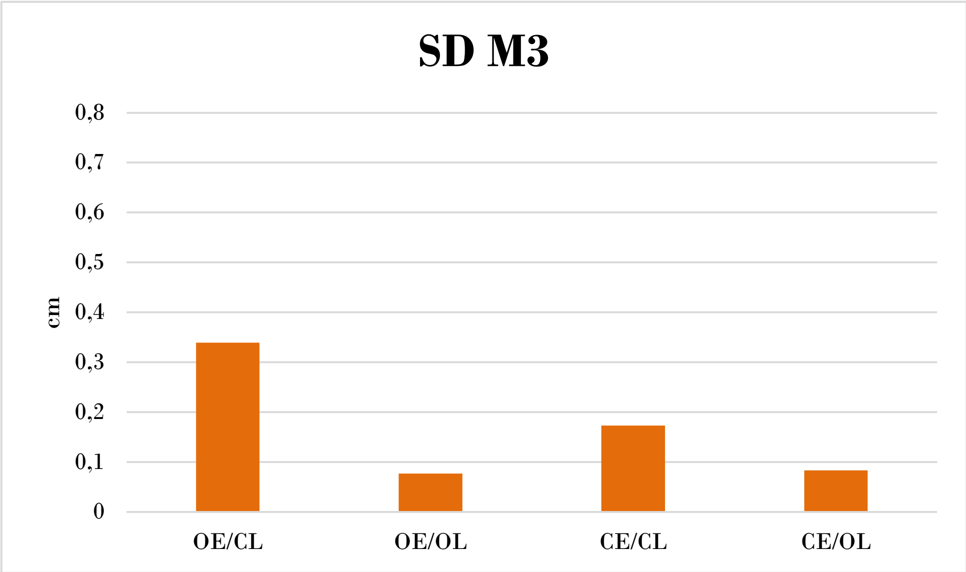


Fig. 5.3.1. Average standard deviation sorted by initial configuration

5.3.2.- Time to peak

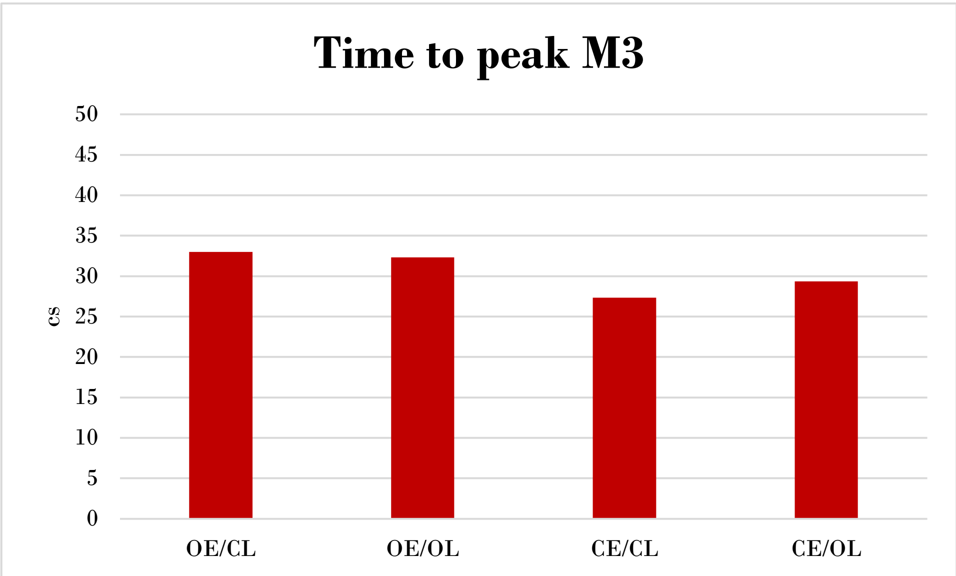


Fig. 5.3.2. Average time to peak sorted by initial configuration

5.3.3.- Force and pressure

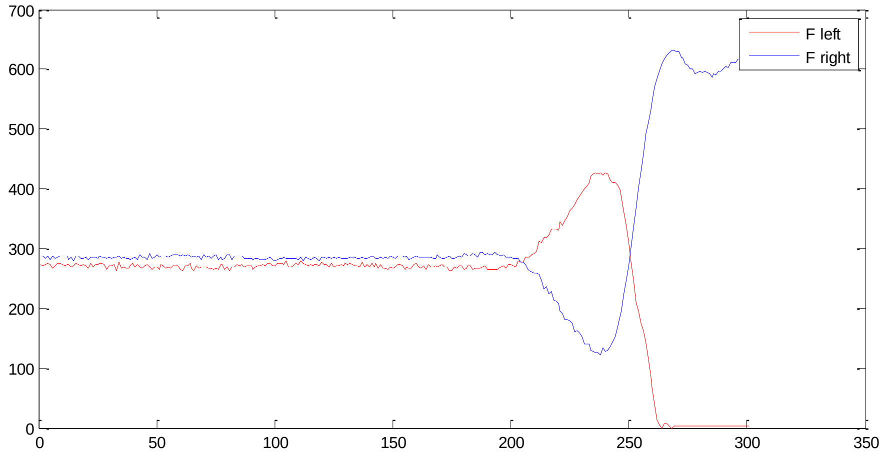


Fig. 5.3.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

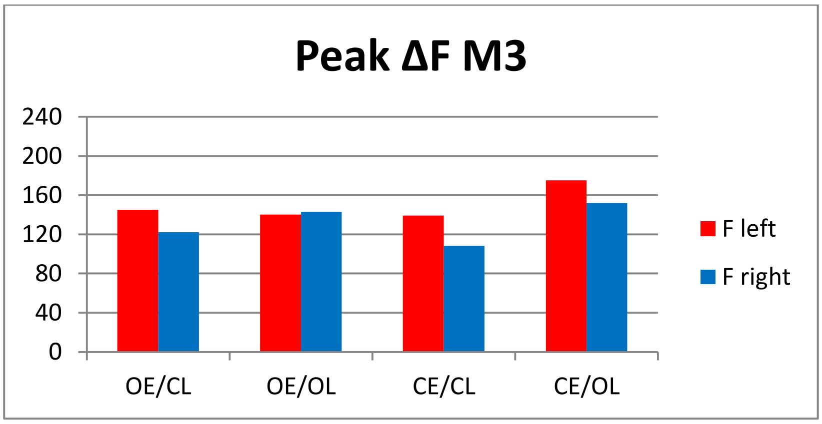


Fig. 5.3.4. Average peak force variation sorted by initial configuration

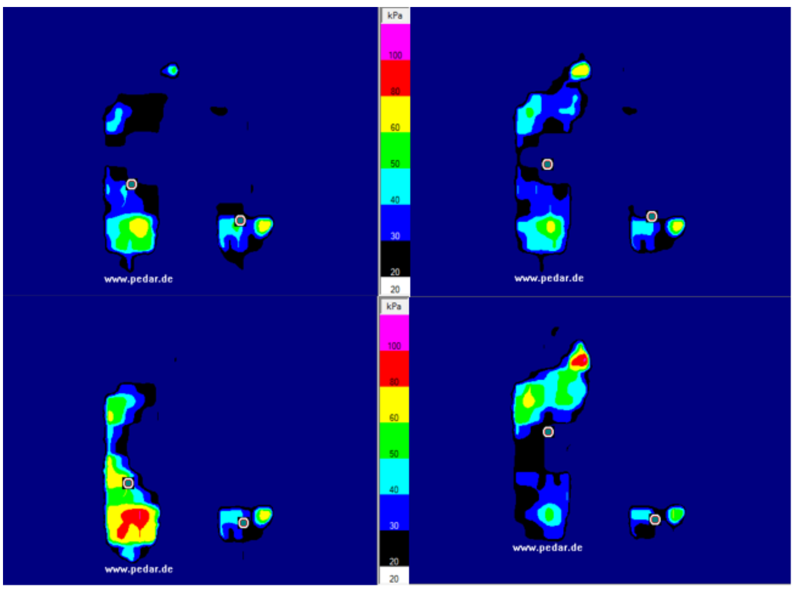


Fig. 5.3.5.Pressure distribution on the feet in the peak M-L CoP displacement moment

5.3.4.- Acceleration and CoP displacement in the medio-lateral direction

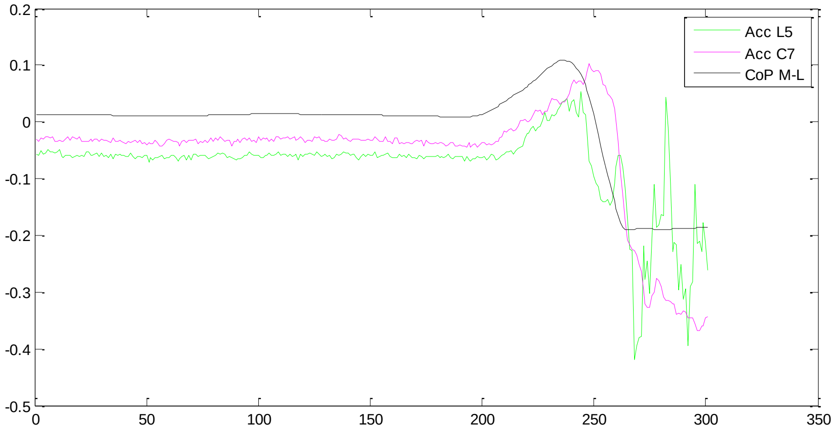


Fig. 5.3.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

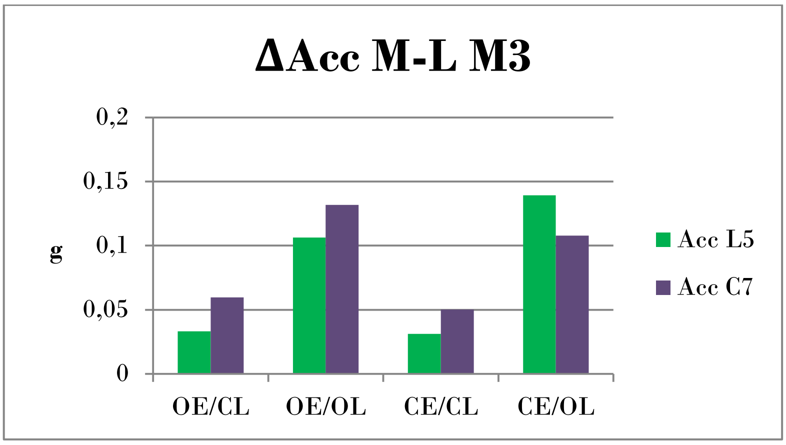


Fig. 5.3.7. Average M-L acceleration variation sorted by initial configuration

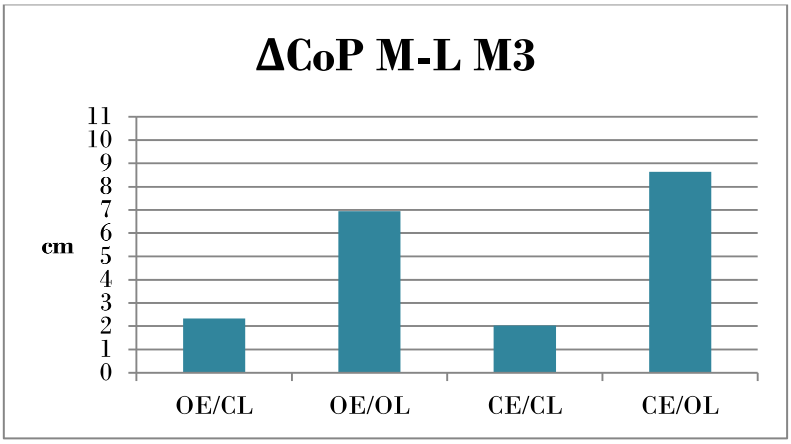


Fig. 5.3.8. Average M-L CoP displacement sorted by initial configuration

5.3.5.- Acceleration and CoP displacement in the antero-posterior direction

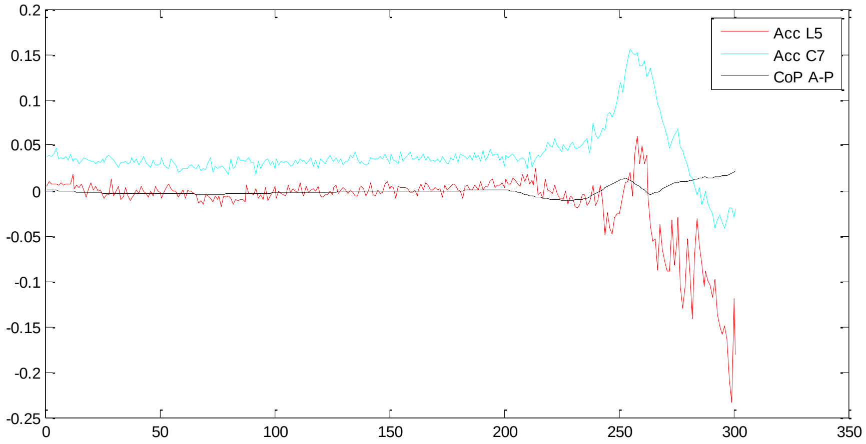


Fig. 5.3.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

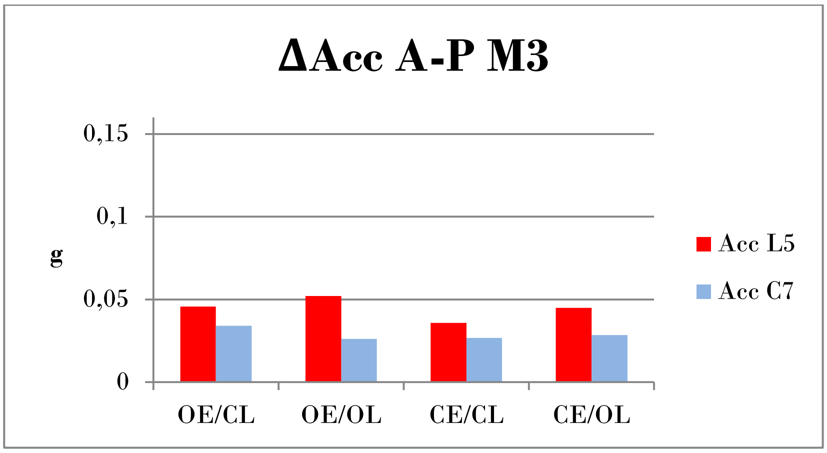


Fig. 5.3.10. Average A-P peak acceleration variation sorted by initial configuration

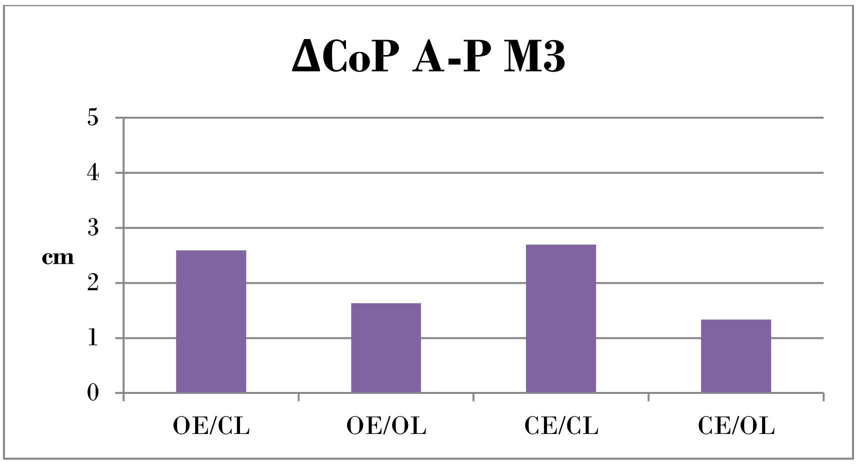


Fig. 5.3.11. Average peak A-P CoP displacement sorted by initial configuration

5.4.- Long step starting with the left leg (M4)

5.4.1.- Standard deviation

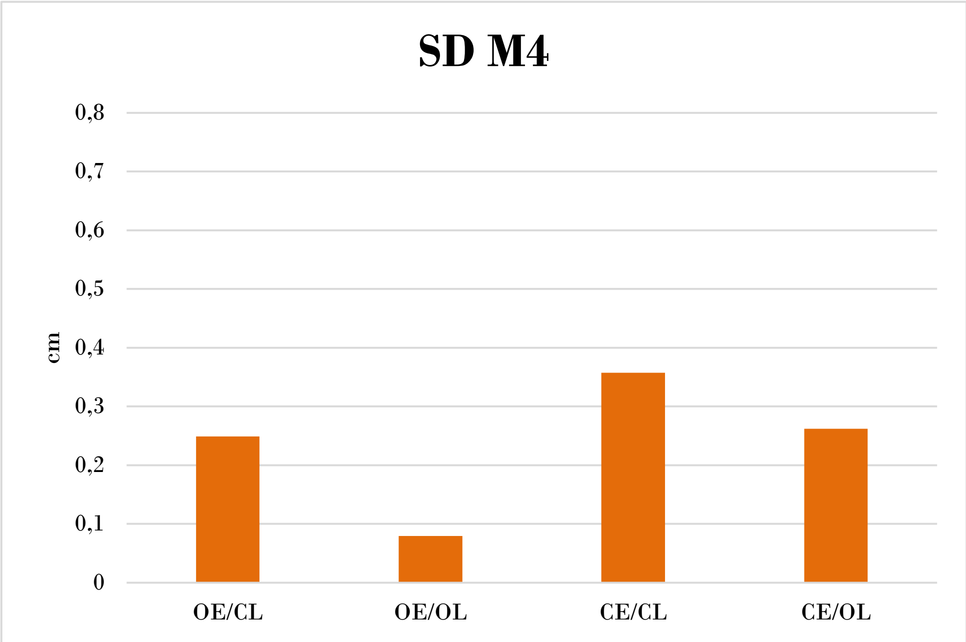


Fig. 5.4.1. Average standard deviation sorted by initial configuration

5.4.2.- Time to peak

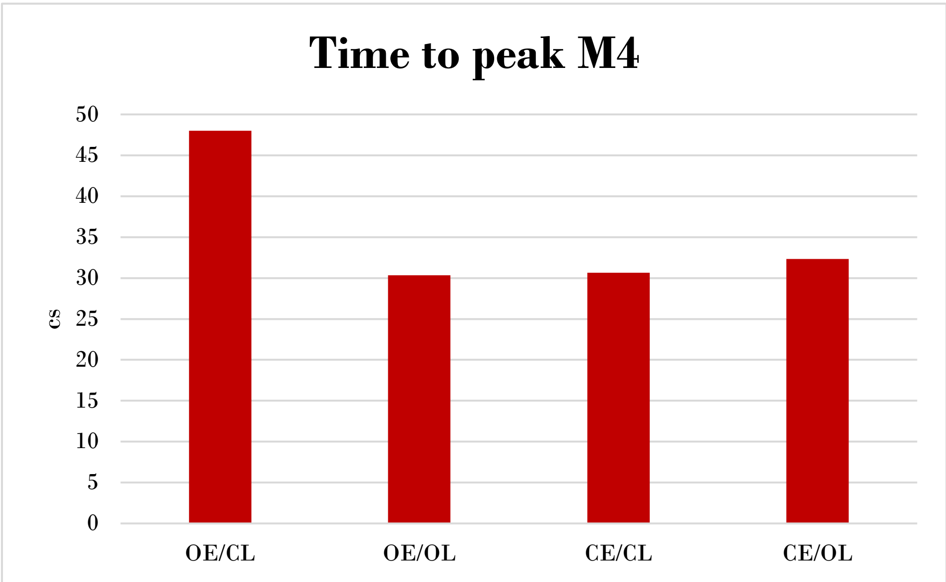


Fig. 5.4.2. Average time to peak sorted by initial configuration

5.4.3.- Force and pressure

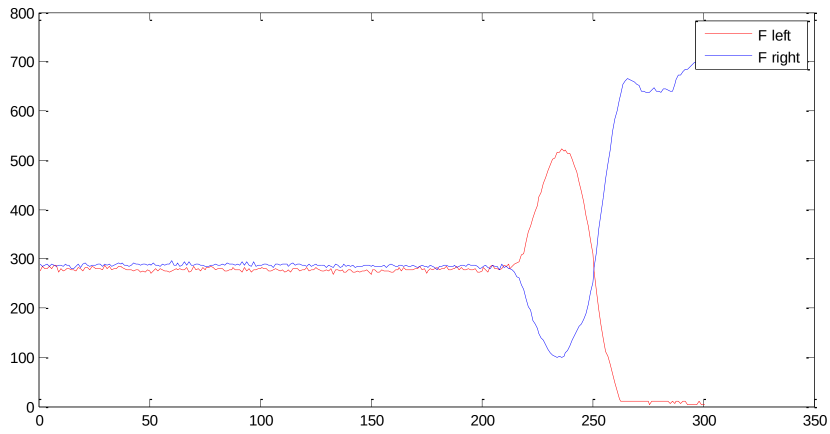


Fig. 5.4.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

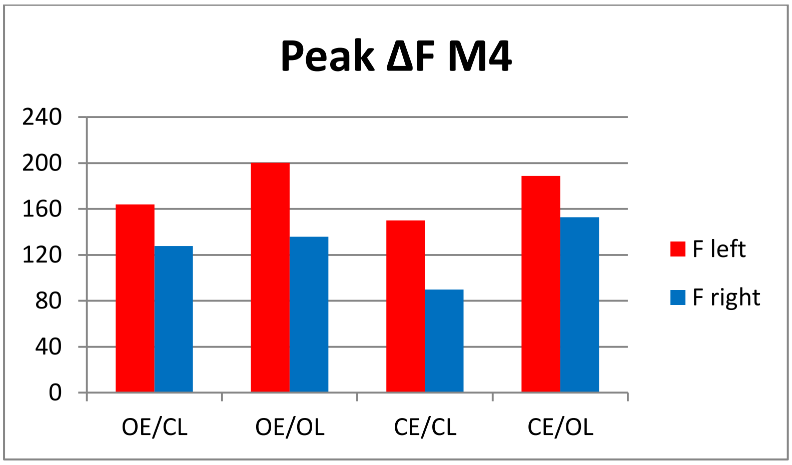


Fig. 5.4.4. Average peak force variation sorted by initial configuration

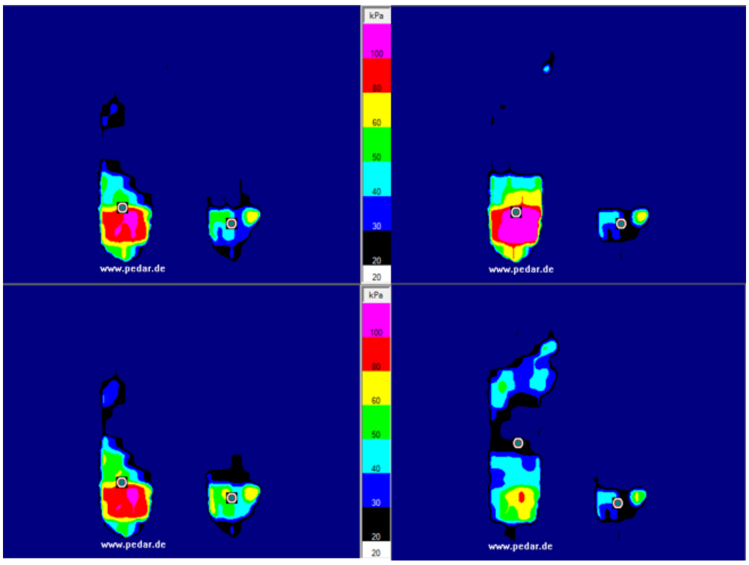


Fig. 5.4.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.4.4.- Acceleration and CoP displacement in the medio-lateral direction

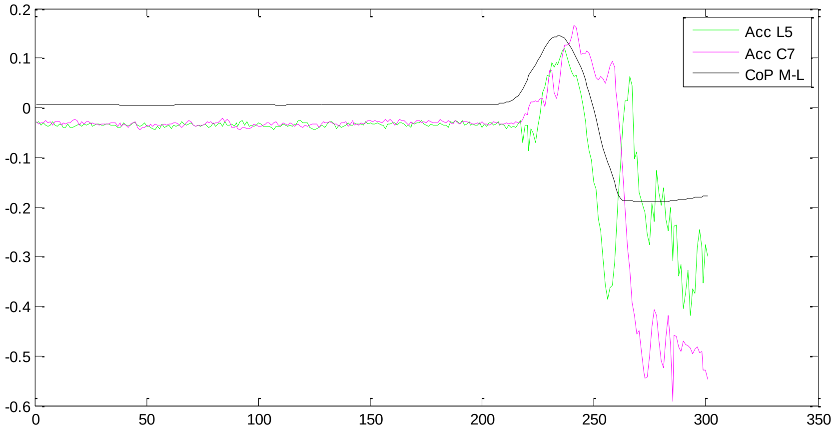


Fig. 5.4.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

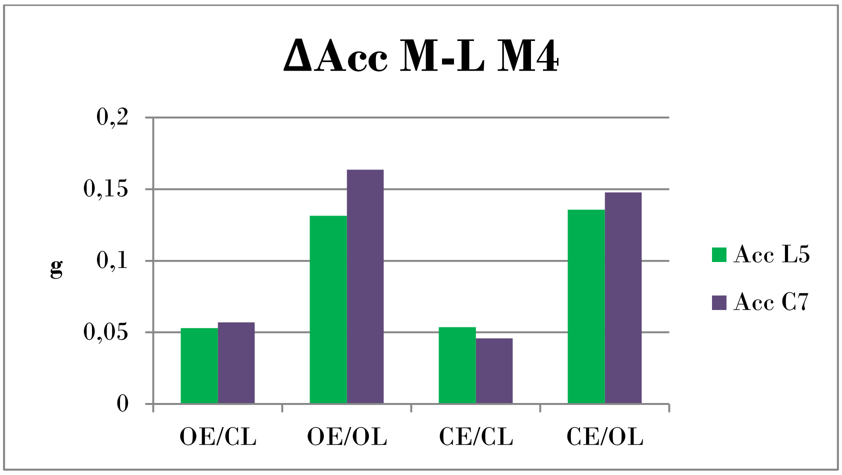


Fig. 5.4.7. Average M-L acceleration variation sorted by initial configuration

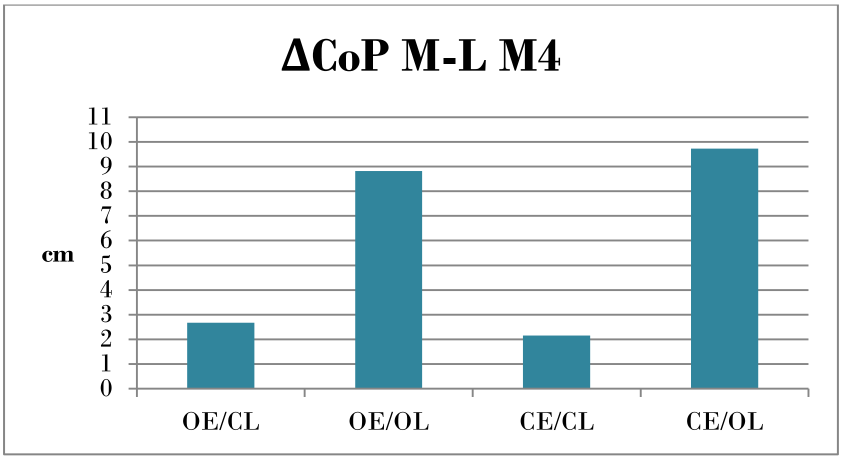


Fig. 5.4.8. Average M-L CoP displacement sorted by initial configuration

5.4.5.- Acceleration and CoP displacement in the antero-posterior direction

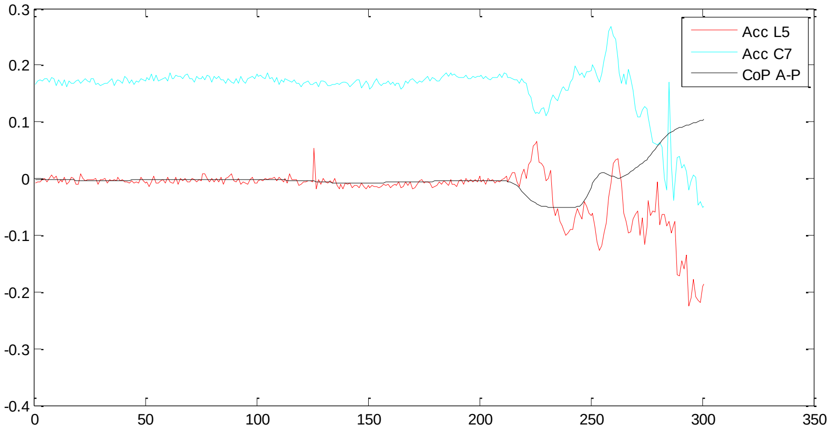


Fig. 5.4.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

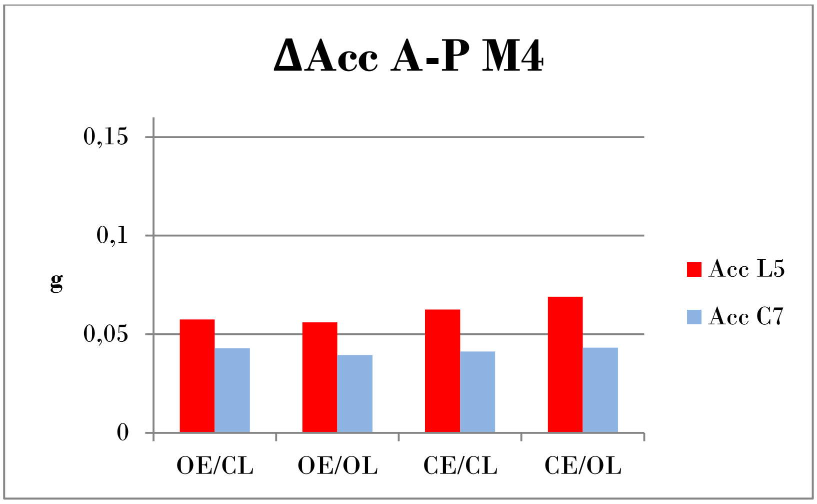


Fig. 5.4.10. Average A-P peak acceleration variation sorted by initial configuration

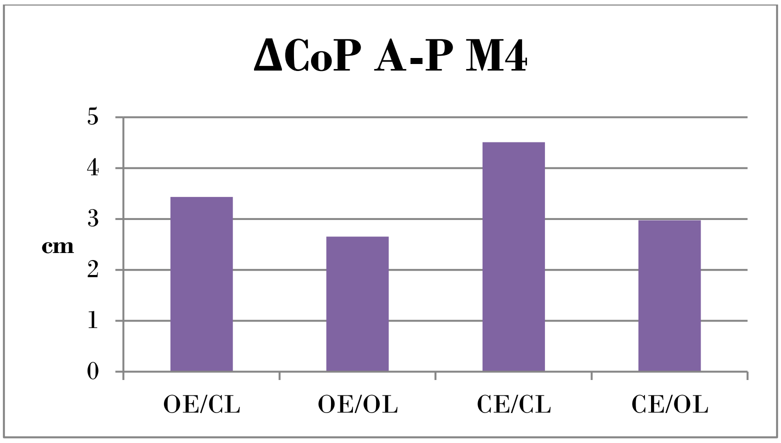


Fig. 5.4.11. Average peak A-P CoP displacement sorted by initial configuration

5.5.- Step back starting with the right leg (M5)

5.5.1.- Standard deviation

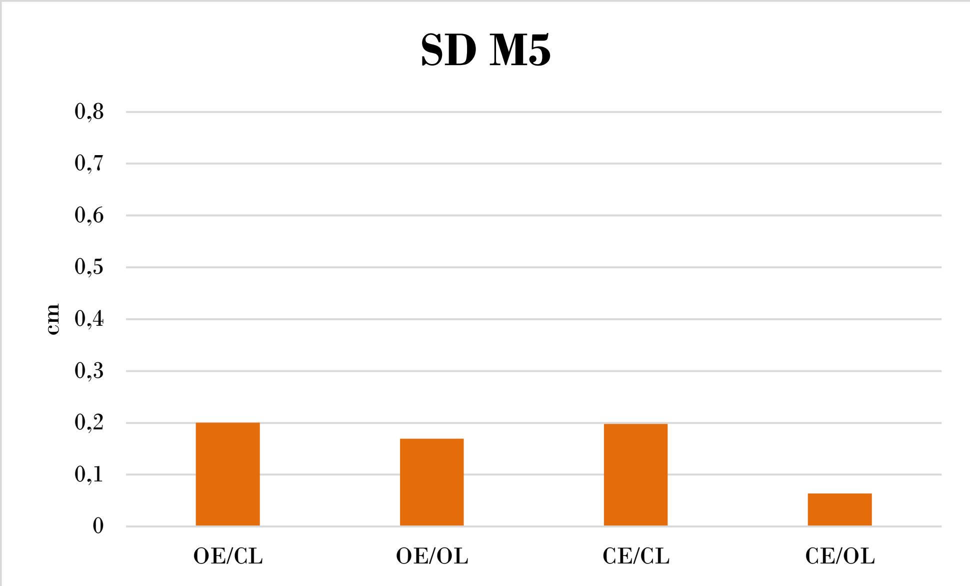


Fig. 5.5.1. Average standard deviation sorted by initial configuration

5.5.2.- Time to peak

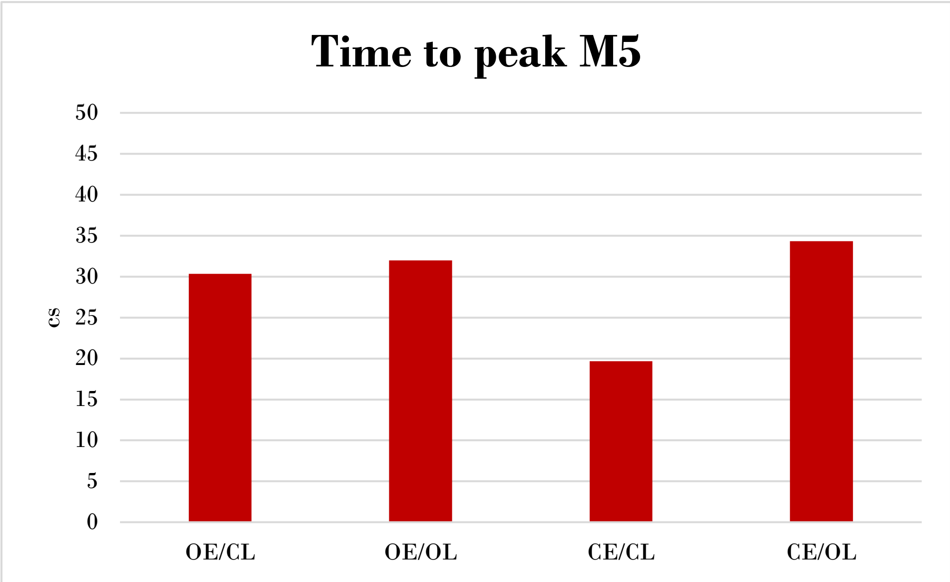


Fig. 5.5.2. Average time to peak sorted by initial configuration

5.5.3.- Force and pressure

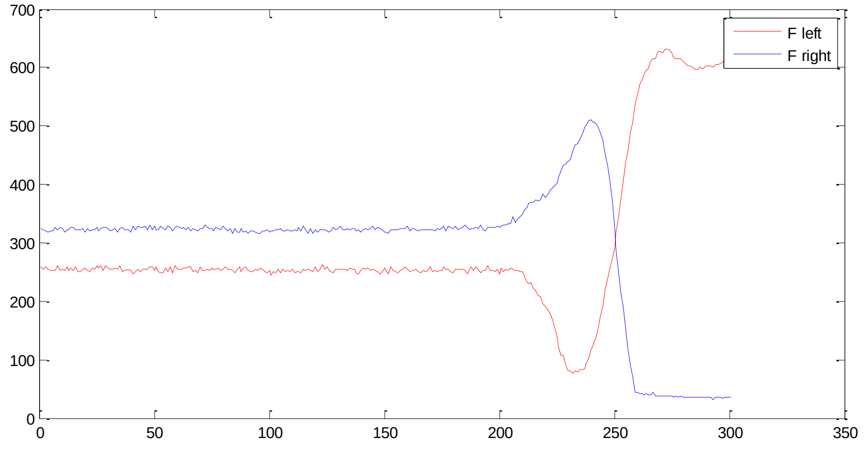


Fig. 5.5.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

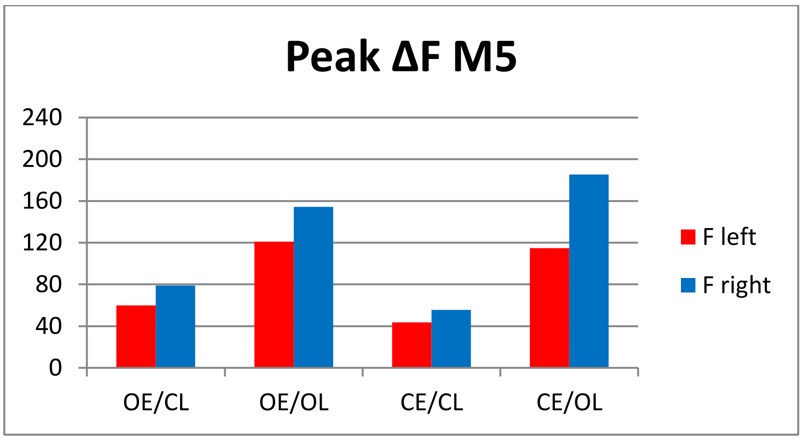


Fig. 5.5.4. Average peak force variation sorted by initial configuration

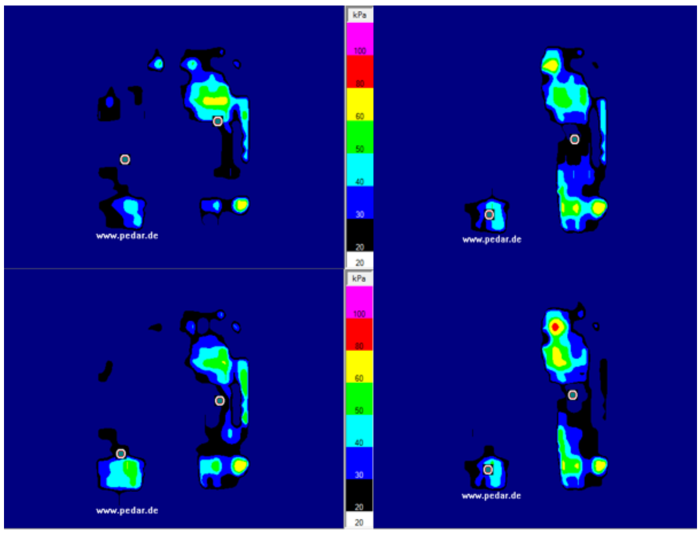


Fig. 5.5.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.5.4.- Acceleration and CoP displacement in the medio-lateral direction

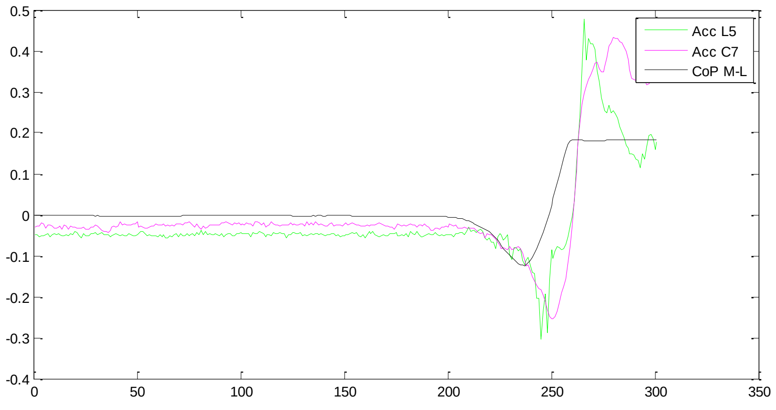


Fig. 5.5.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

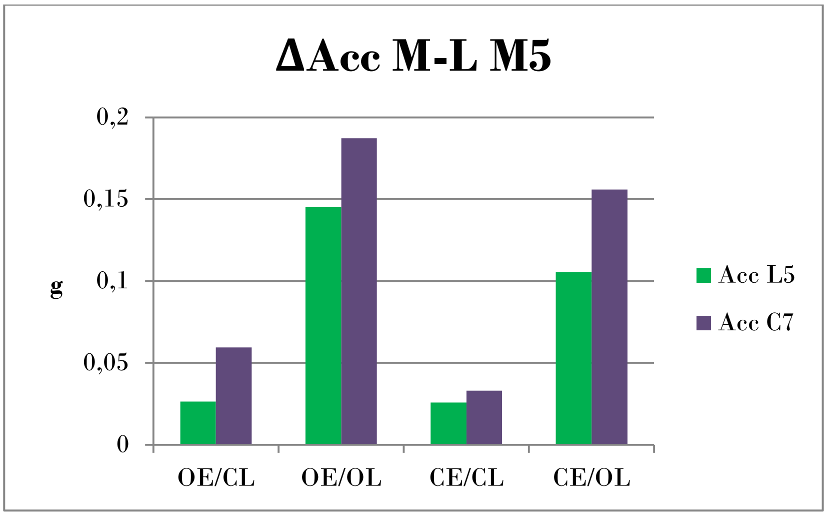


Fig. 5.5.7. Average M-L acceleration variation sorted by initial configuration

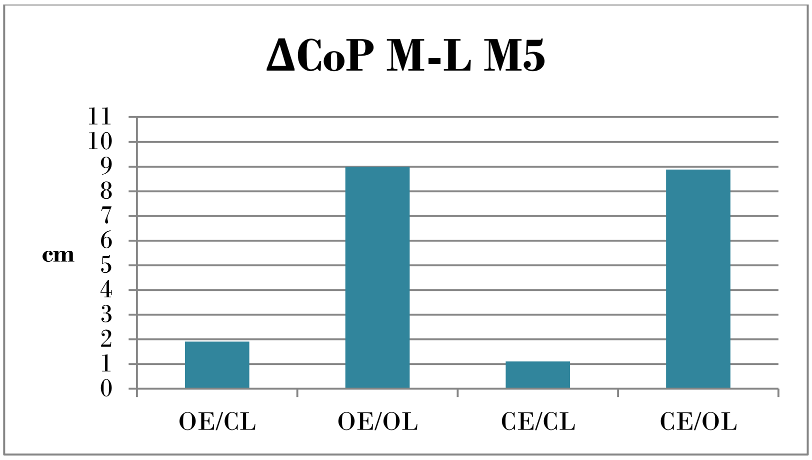


Fig. 5.5.8. Average M-L CoP displacement sorted by initial configuration

5.5.5.- Acceleration and CoP displacement in the antero-posterior direction

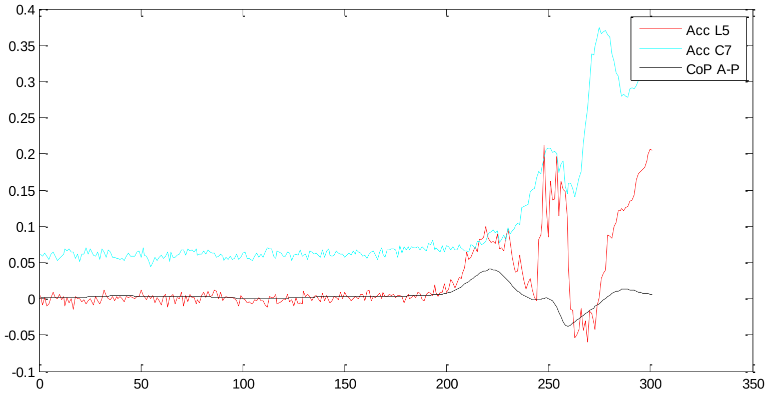


Fig. 5.5.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

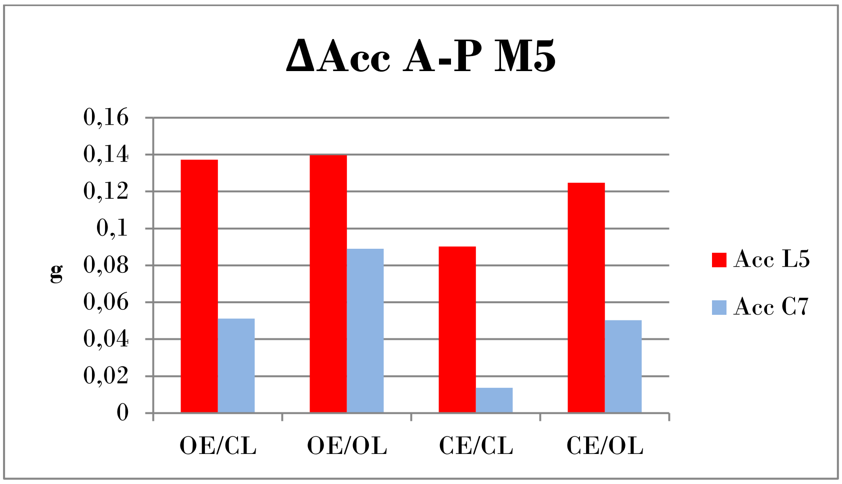


Fig. 5.5.10. Average A-P peak acceleration variation sorted by initial configuration

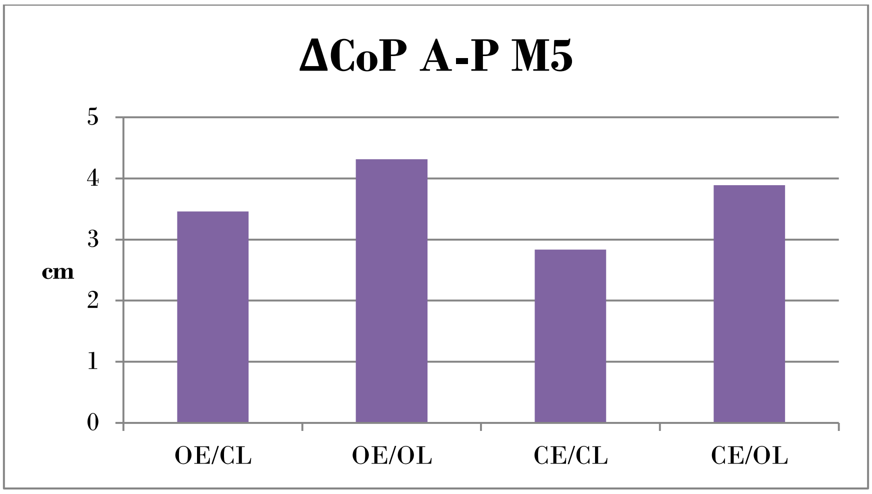


Fig. 5.5.11. Average peak A-P CoP displacement sorted by initial configuration

5.6.- Step back starting with the left leg (M6)

5.6.1.- Standard deviation

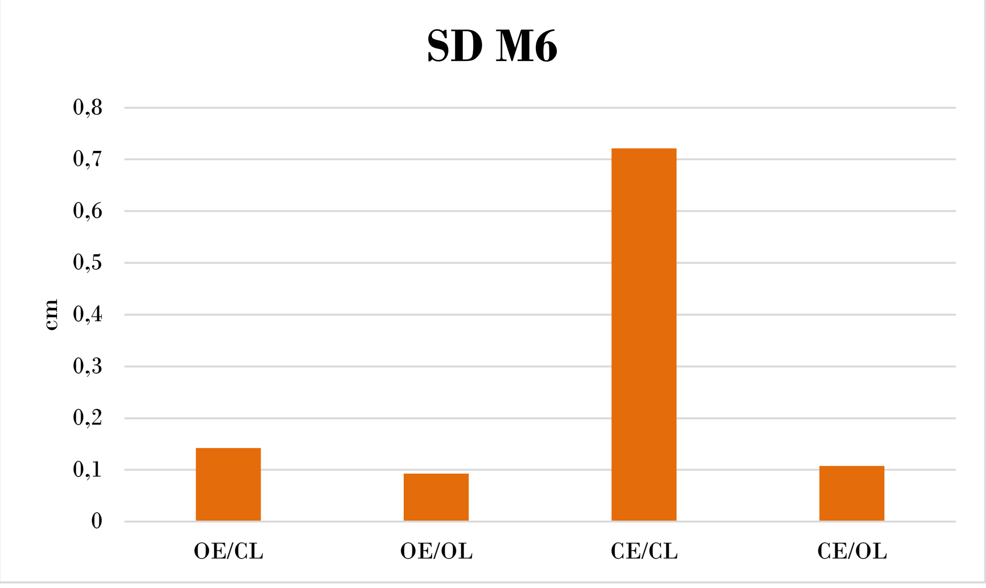


Fig. 5.6.1 Average standard deviation sorted by initial configuration

5.6.2.- Time to peak

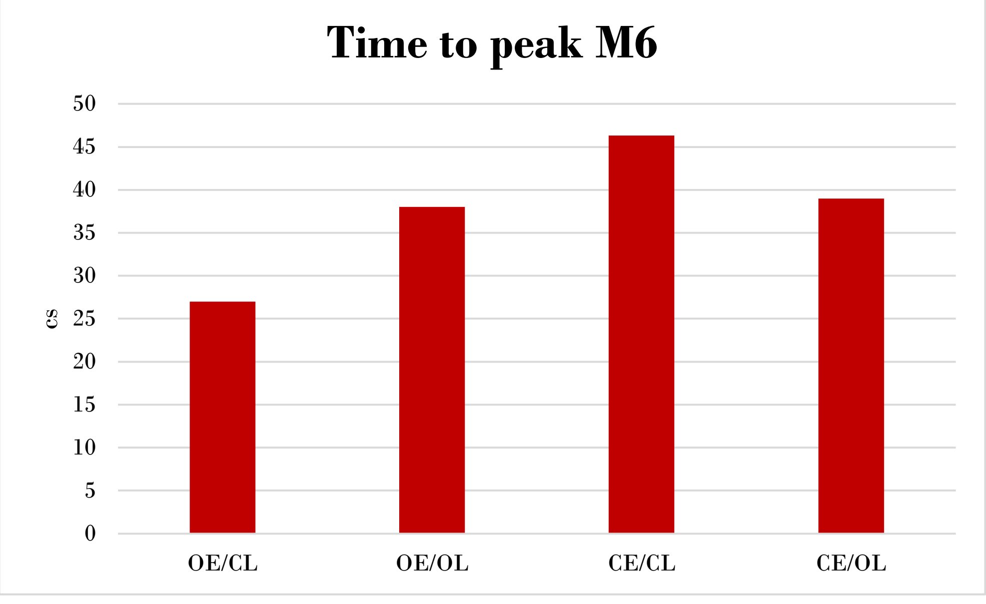


Fig. 5.6.2. Average time to peak sorted by initial configuration

5.6.3.- Force and pressure

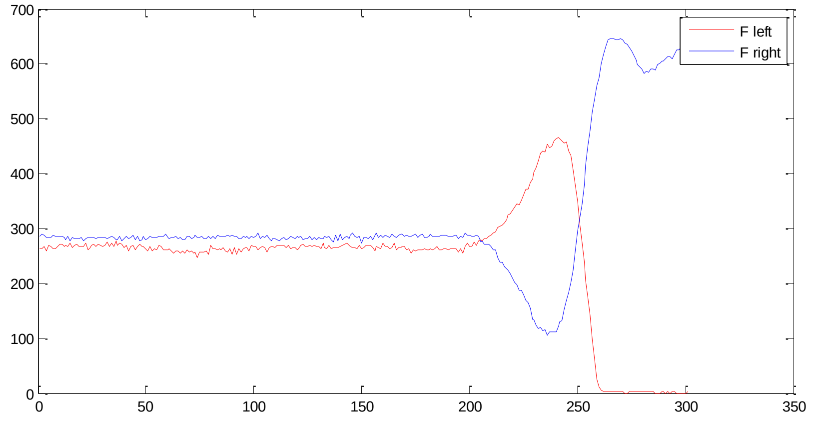


Fig. 5.6.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

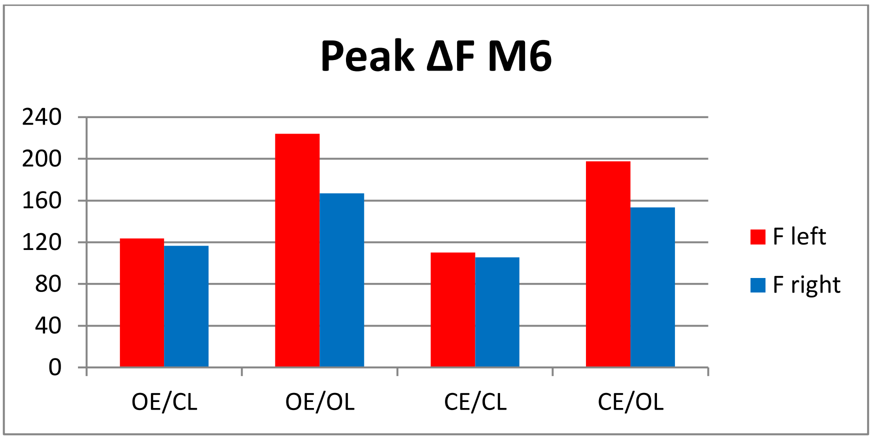


Fig. 5.6.4. Average peak force variation sorted by initial configuration

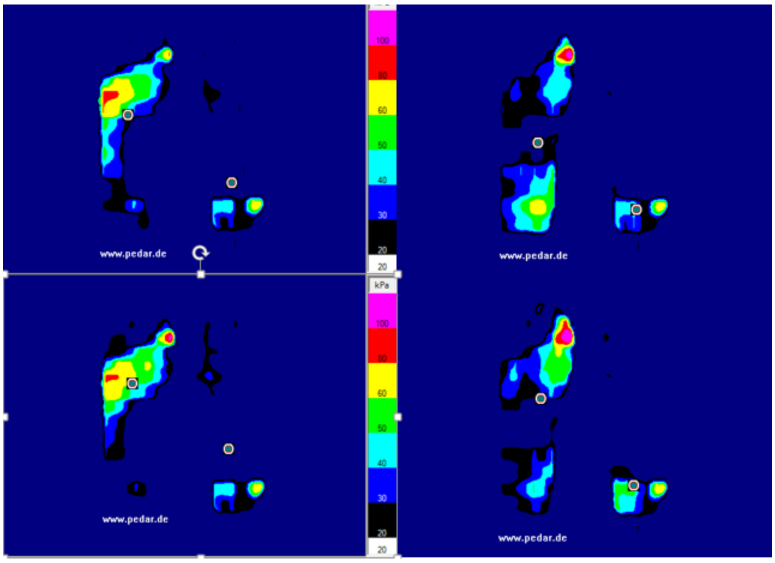


Fig. 5.6.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.6.4.- Acceleration and CoP displacement in the medio-lateral direction

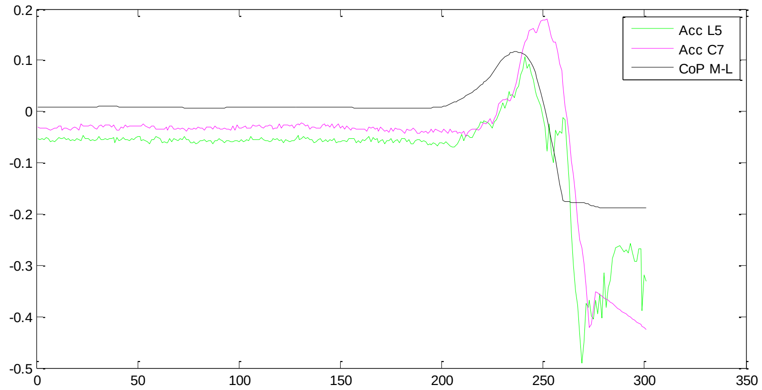


Fig. 5.6.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

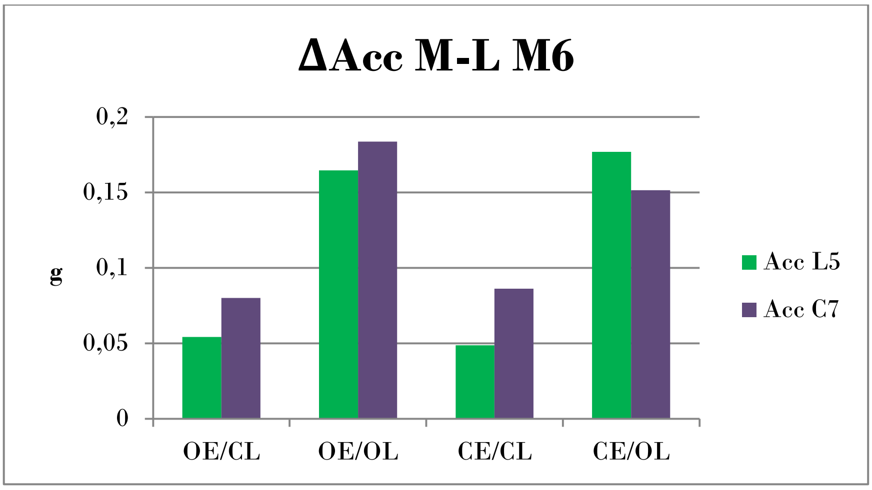


Fig. 5.6.7. Average M-L acceleration variation sorted by initial configuration

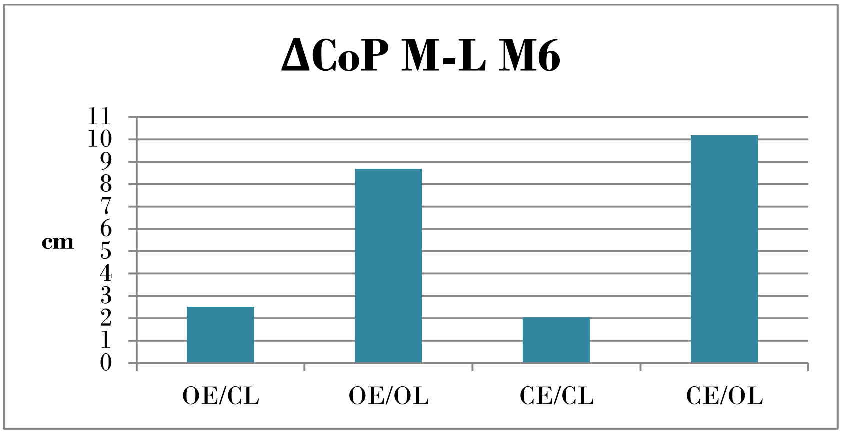


Fig. 5.6.8. Average M-L CoP displacement sorted by initial configuration

5.6.5.- Acceleration and CoP displacement in the antero-posterior direction

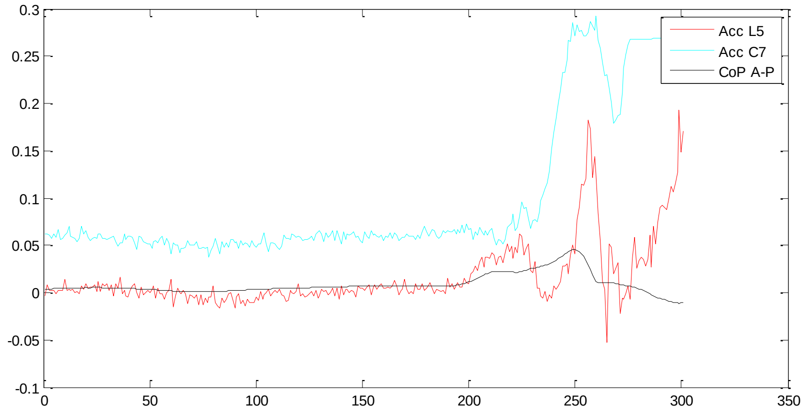


Fig.5.6.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

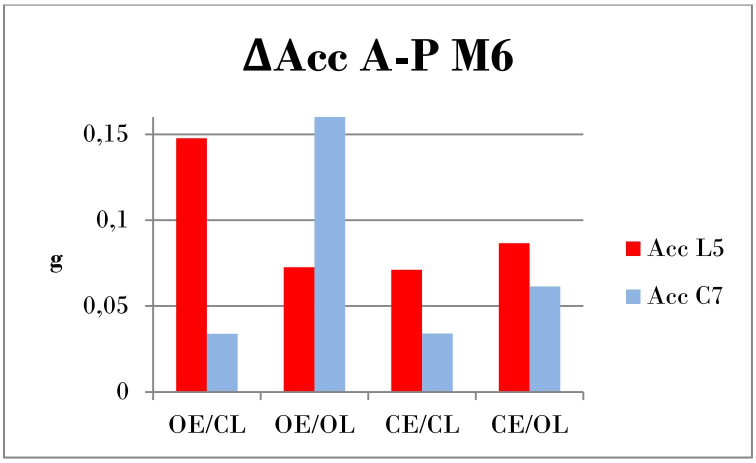


Fig. 5.6.10. Average A-P peak acceleration variation sorted by initial configuration

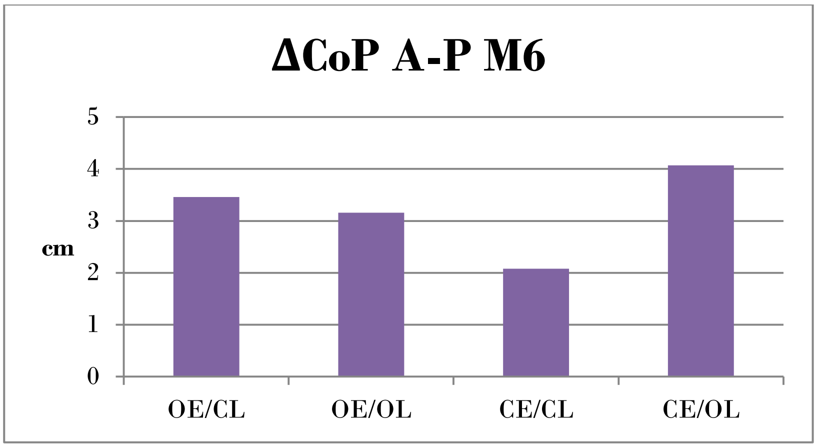


Fig. 5.6.11. Average peak A-P CoP displacement sorted by initial configuration

5.7.- Standing on the left leg (M7)

5.7.1.- Standard deviation

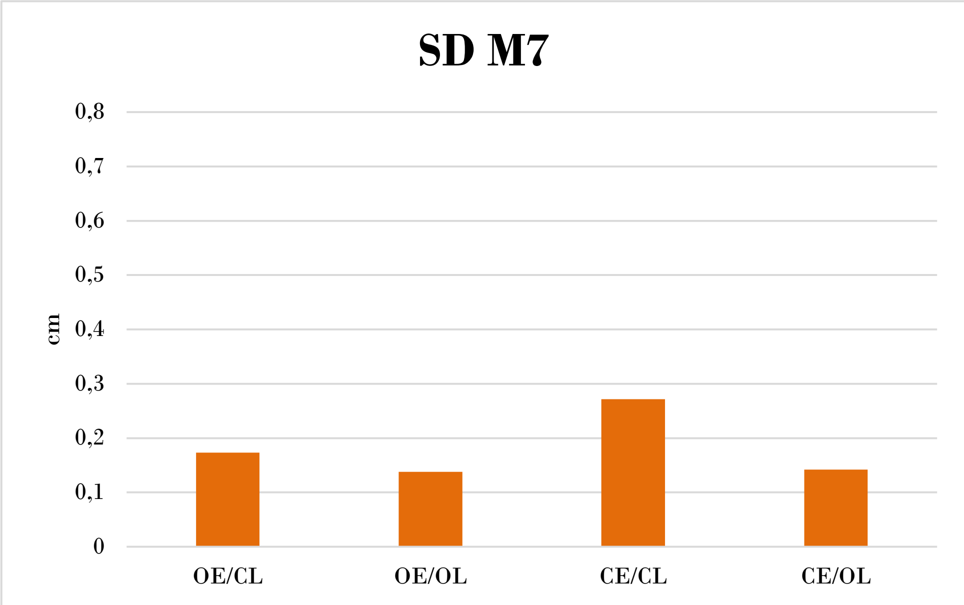


Fig. 5.7.1. Average standard deviation sorted by initial configuration

5.7.2.- Time to peak

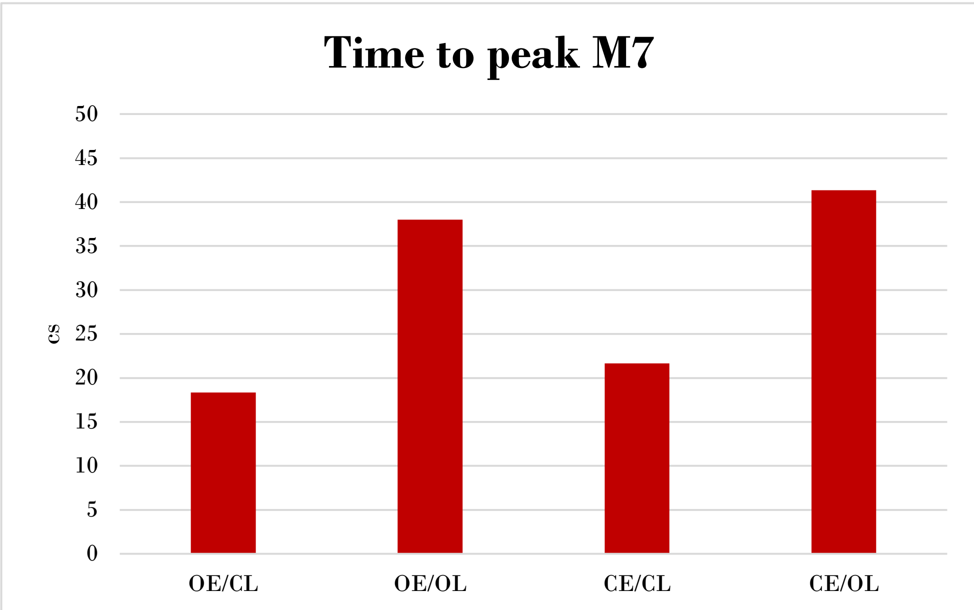


Fig. 5.7.2. Average time to peak sorted by initial configuration

5.7.3.- Force and pressure

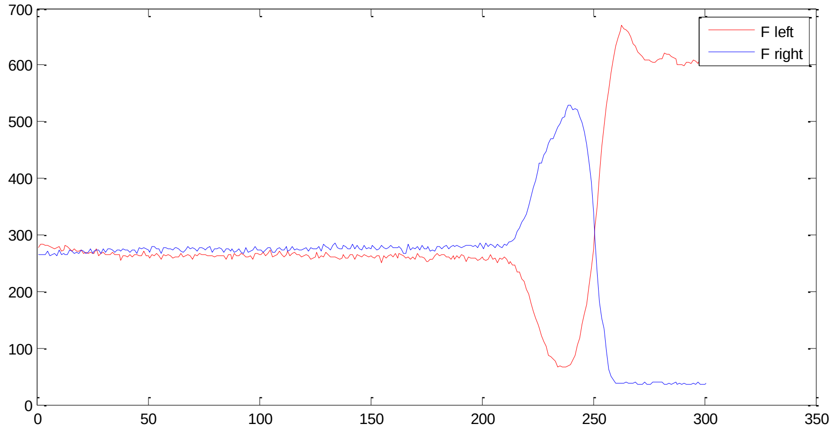


Fig. 5.7.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

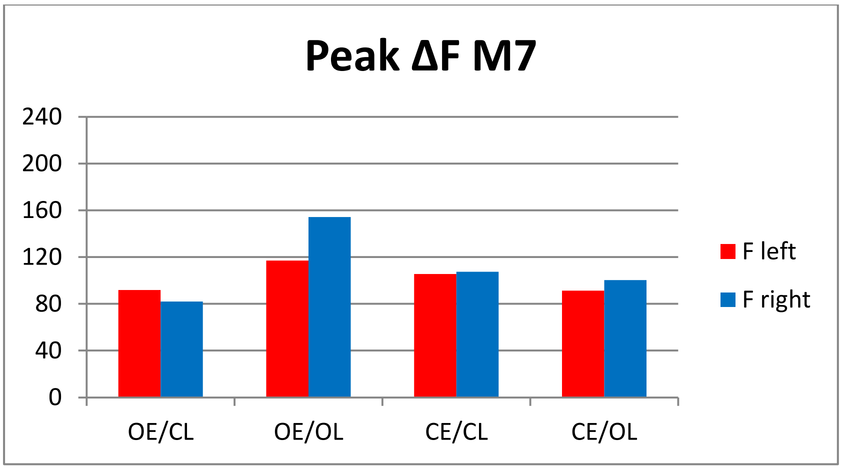


Fig. 5.7.4. Average peak force variation sorted by initial configuration

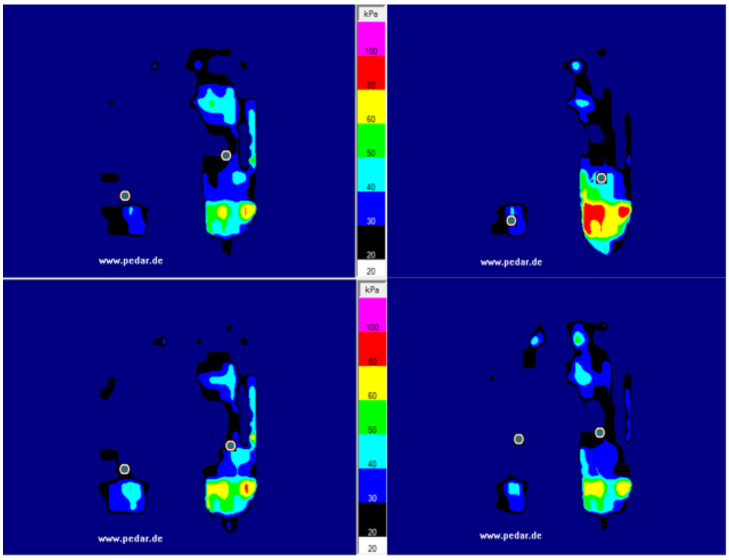


Fig. 5.7.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.7.4.- Acceleration and CoP displacement in the medio-lateral direction

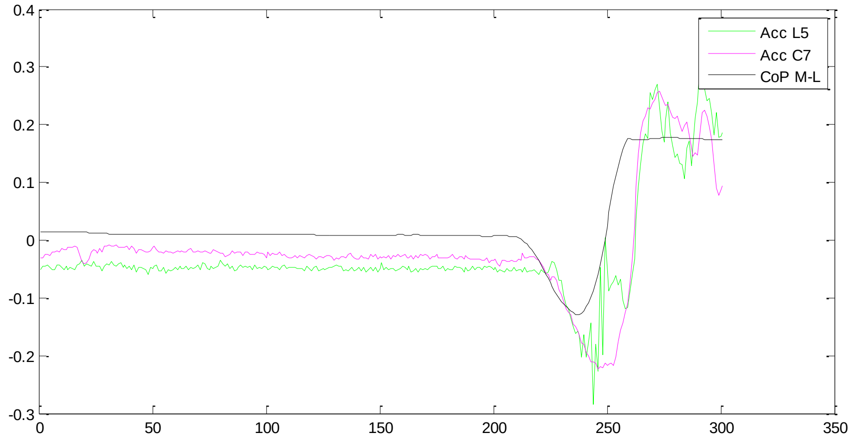


Fig. 5.7.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

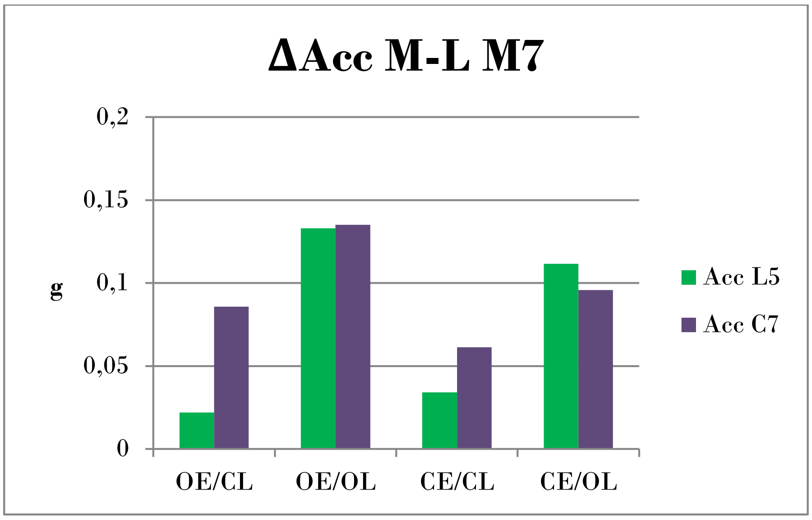


Fig.5.7.7. Average M-L acceleration variation sorted by initial configuration

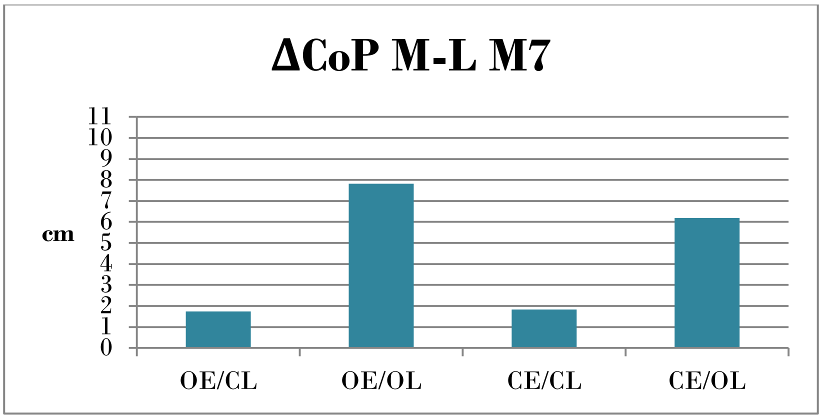


Fig. 5.7.8. Average M-L CoP displacement sorted by initial configuration

5.7.5.- Acceleration and CoP displacement in the antero-posterior direction

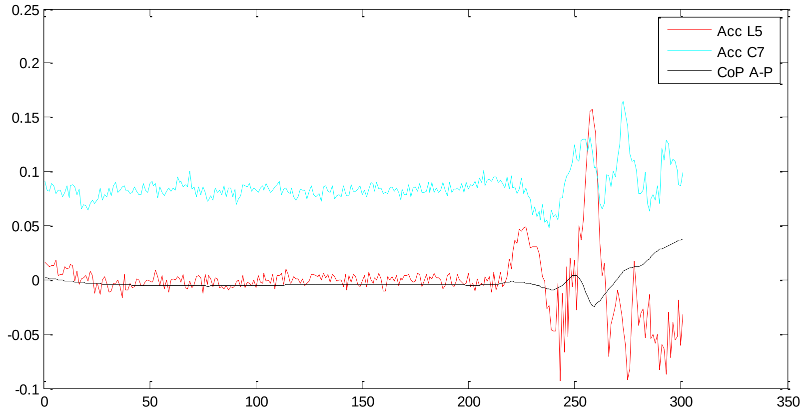


Fig. 5.7.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

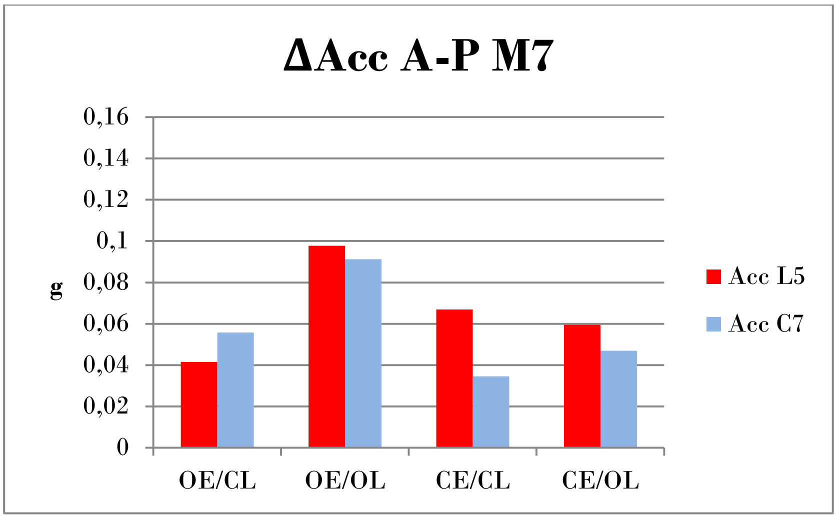


Fig. 5.7.10. Average A-P peak acceleration variation sorted by initial configuration

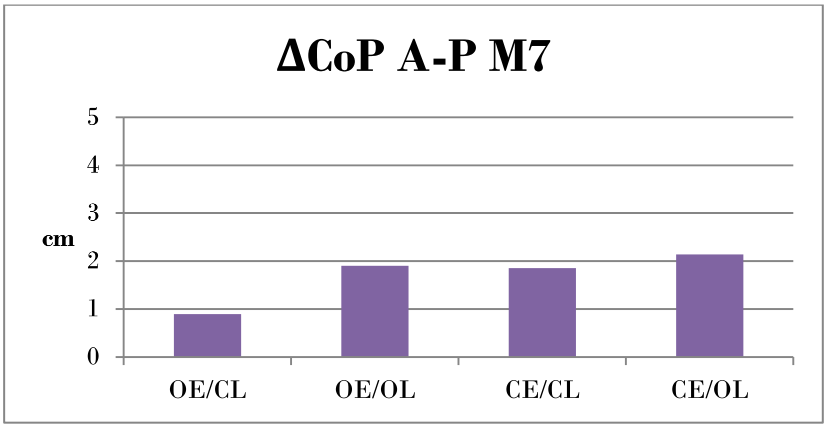


Fig. 5.7.11. Average peak A-P CoP displacement sorted by initial configuration

5.8.- Standing on the right leg (M8)

5.8.1.- Standard deviation

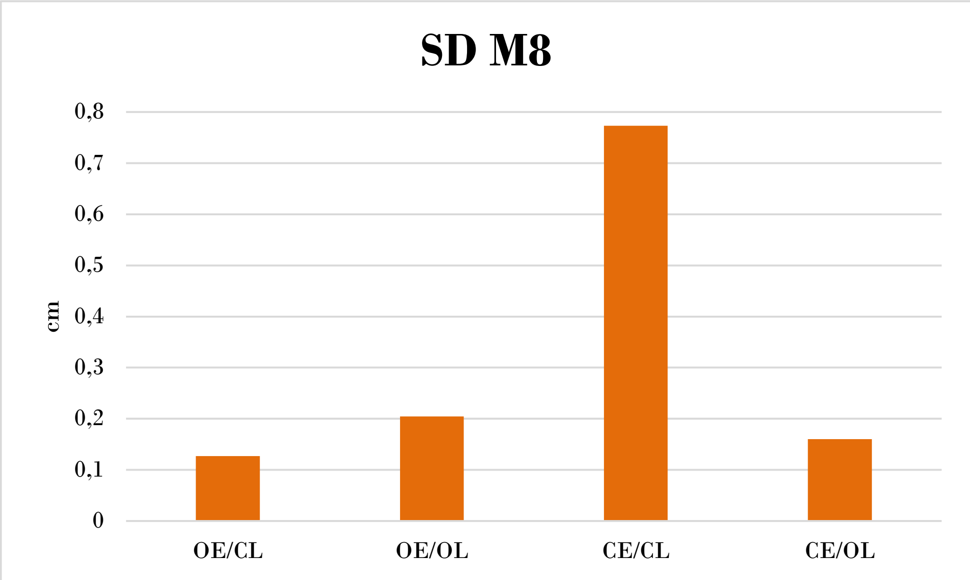


Fig. 5.8.1. Average standard deviation sorted by initial configuration

5.8.2.- Time to peak

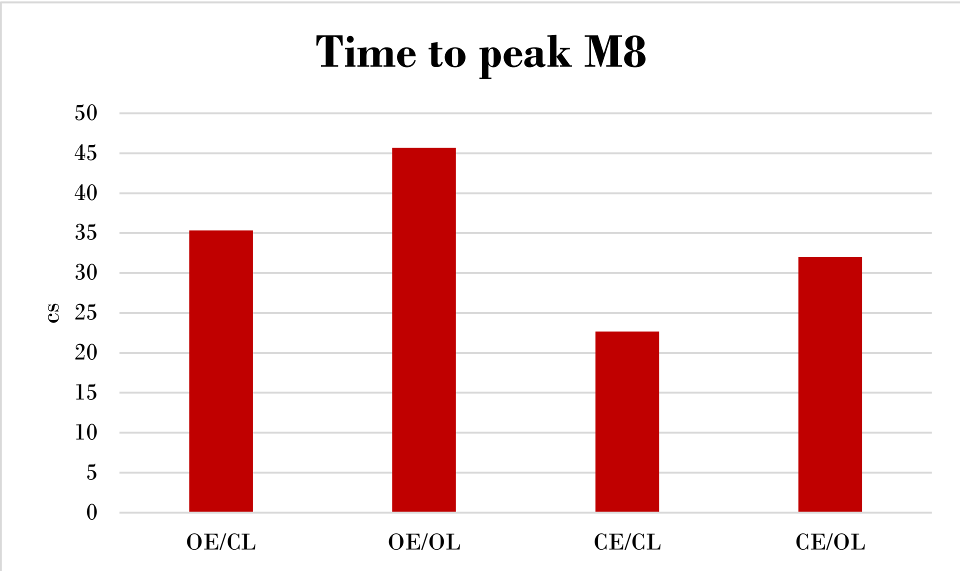


Fig. 5.8.2. Average time to peak sorted by initial configuration

5.8.3.- Force and pressure

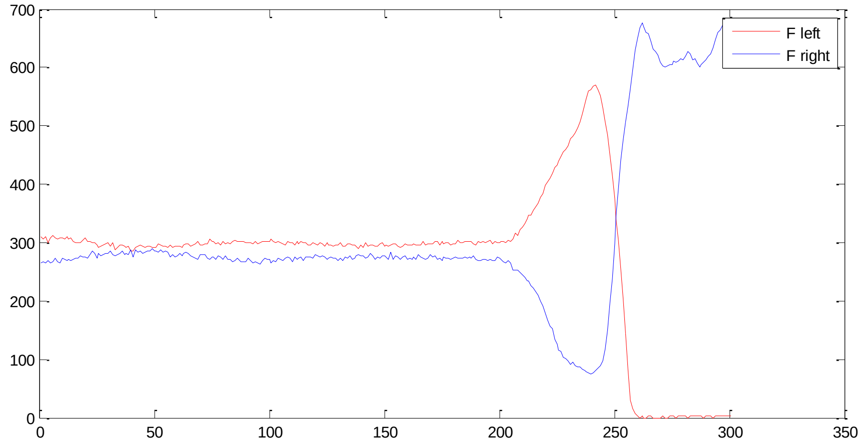


Fig. 5.8.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

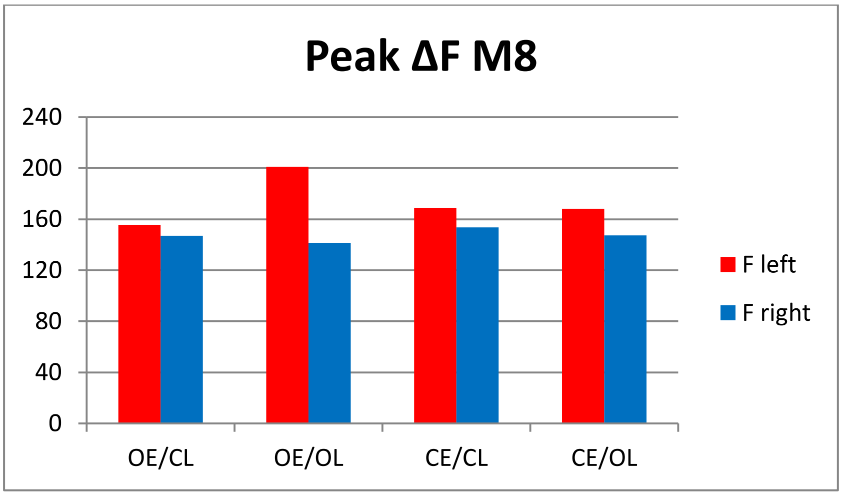


Fig. 5.8.4. Average peak force variation sorted by initial configuration

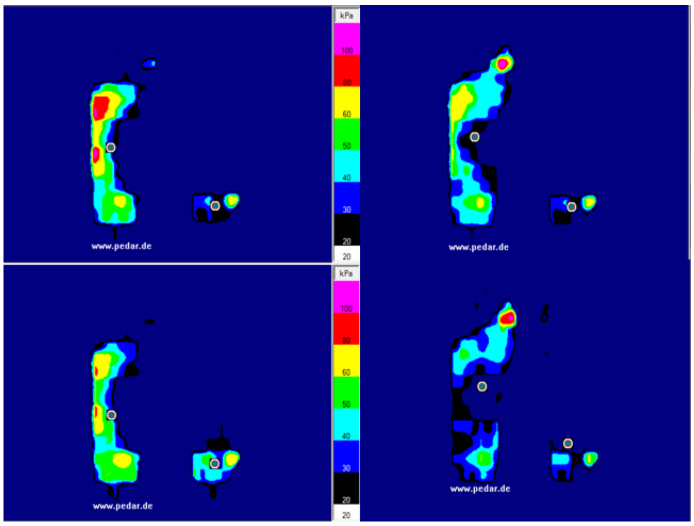


Fig. 5.8.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.8.4.- Acceleration and CoP displacement in the medio-lateral direction

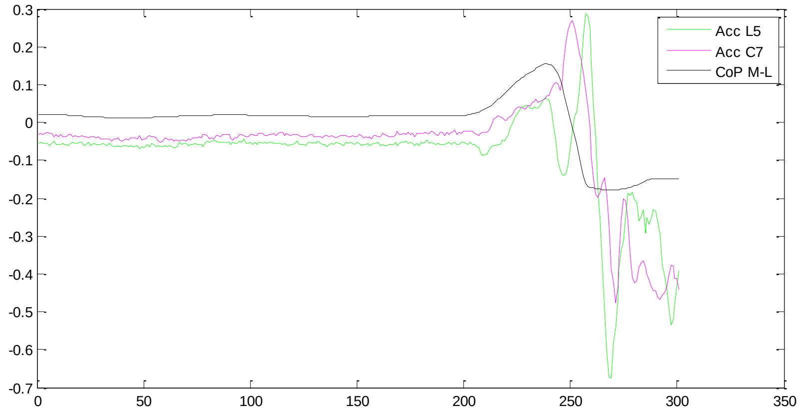


Fig. 5.8.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

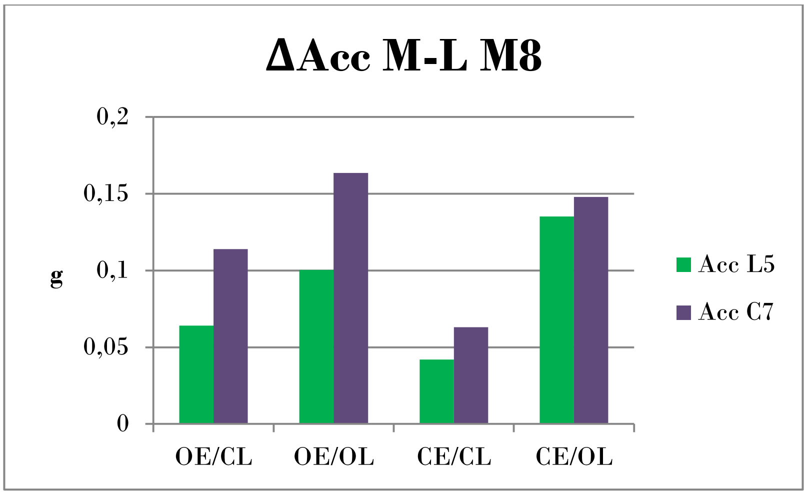


Fig. 5.8.7. Average M-L acceleration variation sorted by initial configuration

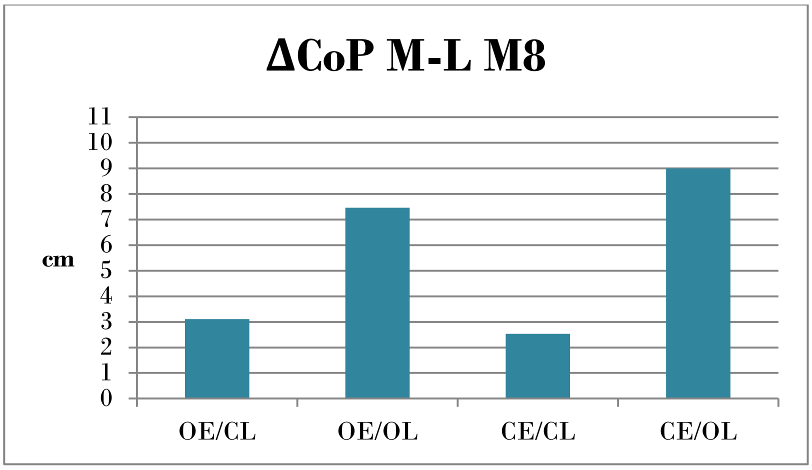


Fig. 5.8.8. Average M-L CoP displacement sorted by initial configuration

5.8.5.- Acceleration and CoP displacement in the antero-posterior direction

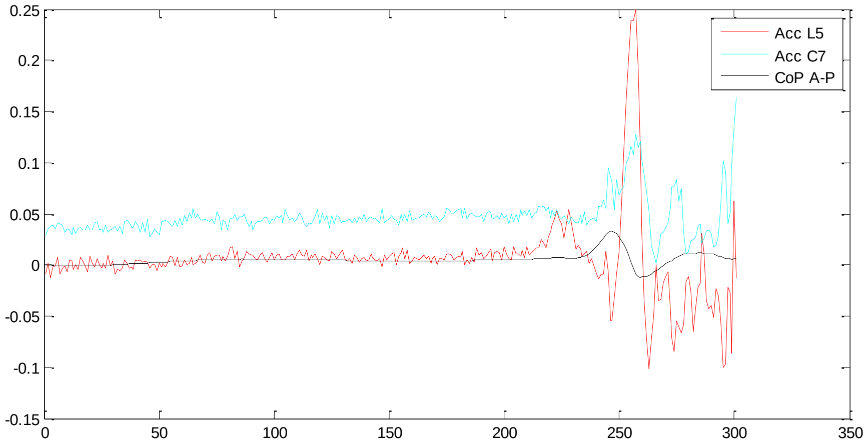


Fig. 5.8.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

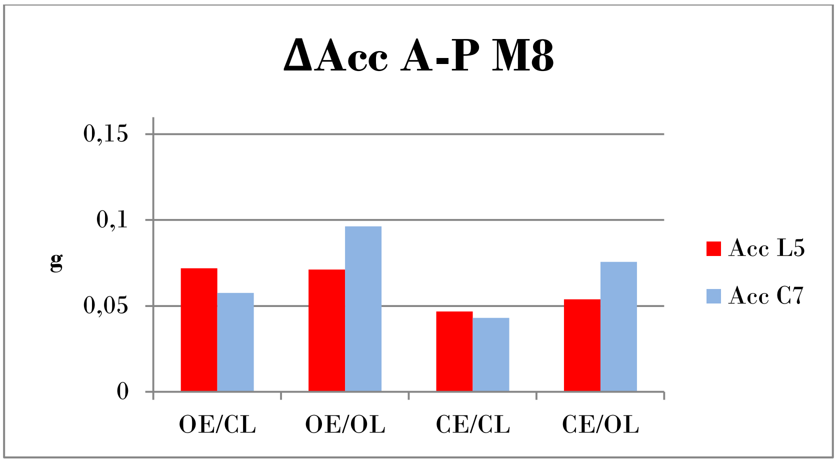


Fig. 5.8.10. Average A-P peak acceleration variation sorted by initial configuration

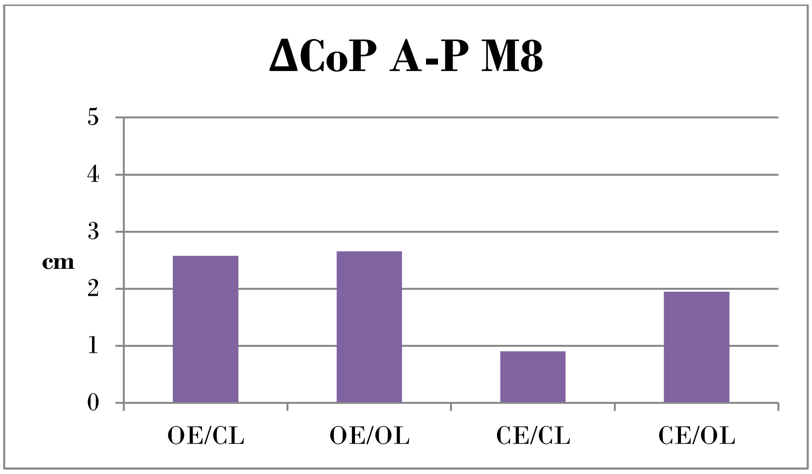


Fig. 5.8.11. Average peak A-P CoP displacement sorted by initial configuratio

5.9.- Turning step to the right (M9)

5.9.1.- Standard deviation

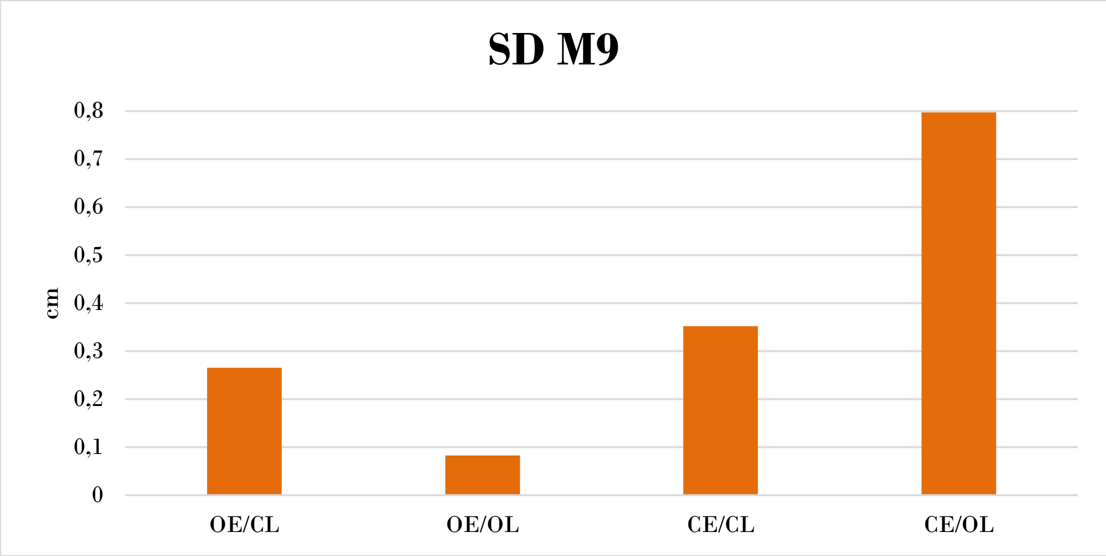


Fig. 5.9.1. Average standard deviation sorted by initial configuration

5.9.2.- Time to peak

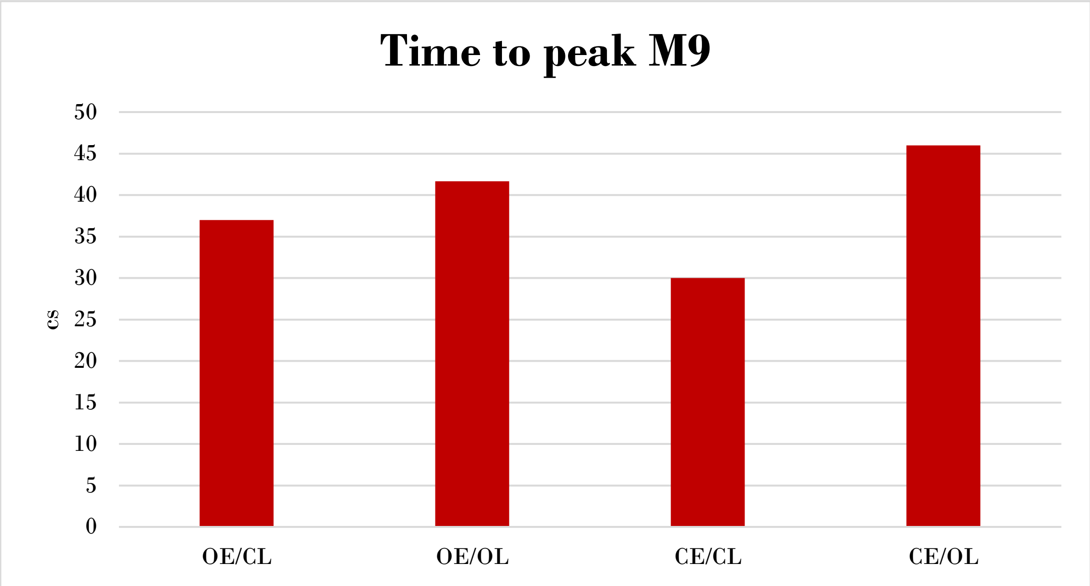


Fig. 5.9.2. Average time to peak sorted by initial configuration

5.9.3.- Force and pressure

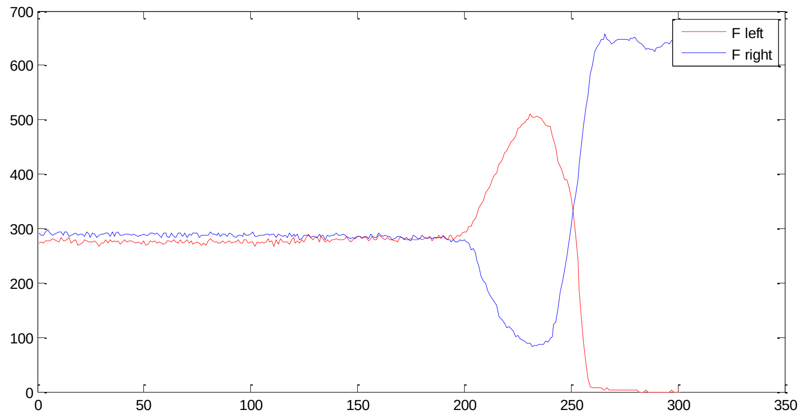


Fig. 5.9.3. Forces (N) on a representative subject before, during and after APA's. Time in cs

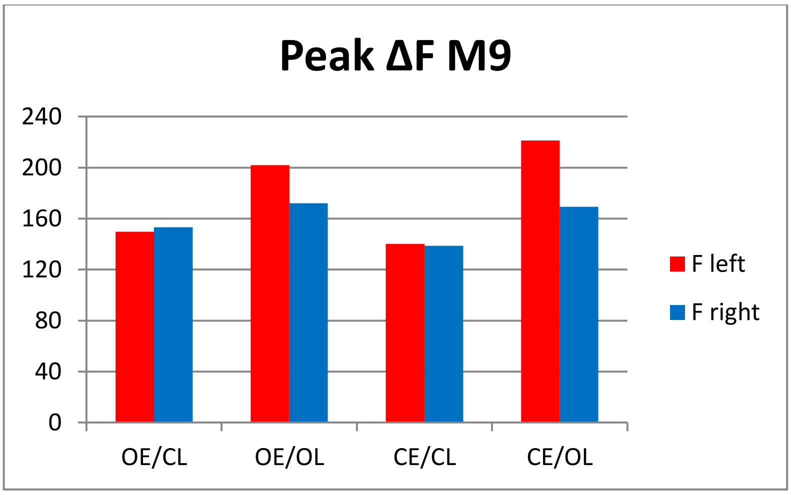


Fig. 5.9.4. Average peak force variation sorted by initial configuration

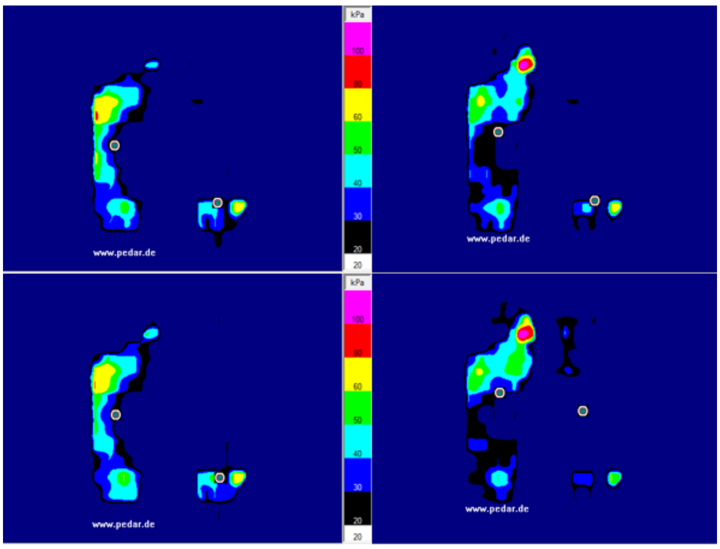


Fig. 5.9.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.9.4.- Acceleration and CoP displacement in the medio-lateral direction

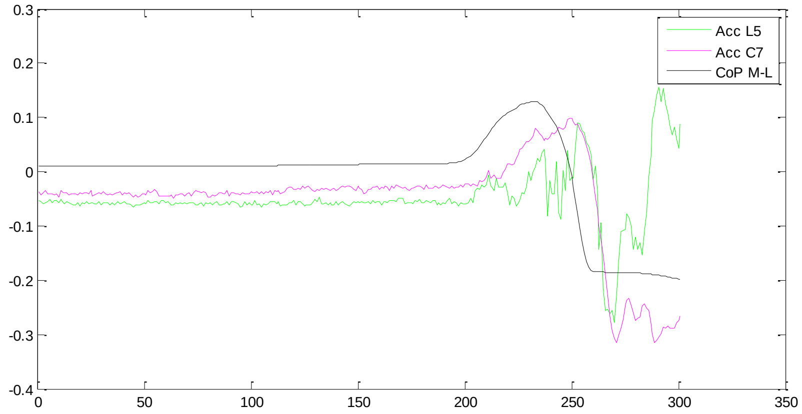


Fig. 5.9.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

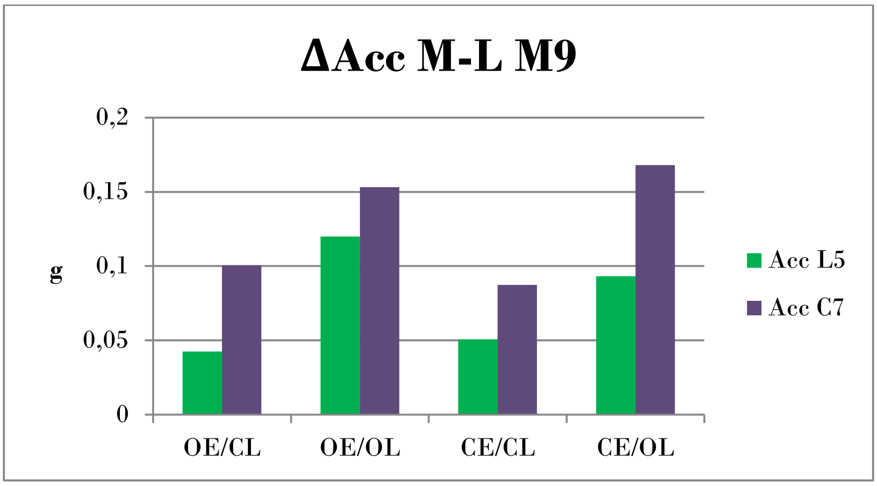


Fig. 5.9.7. Average M-L acceleration variation sorted by initial configuration

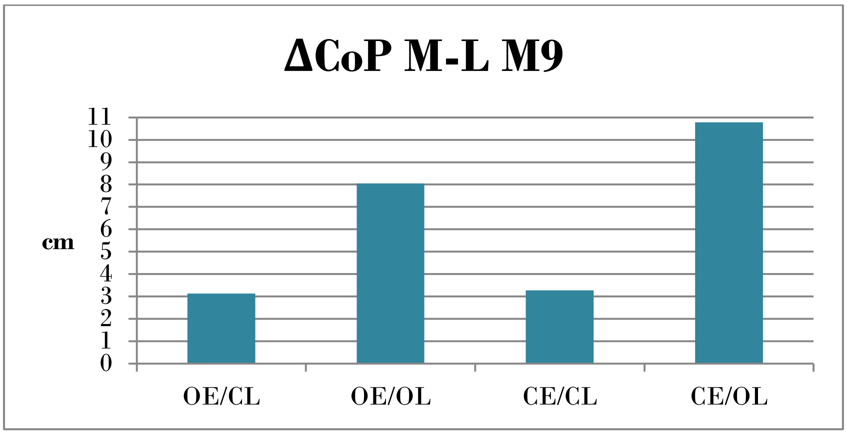


Fig. 5.9.8. Average peak M-L CoP displacement sorted by initial configuration

5.9.5.- Acceleration and CoP displacement in the antero-posterior direction

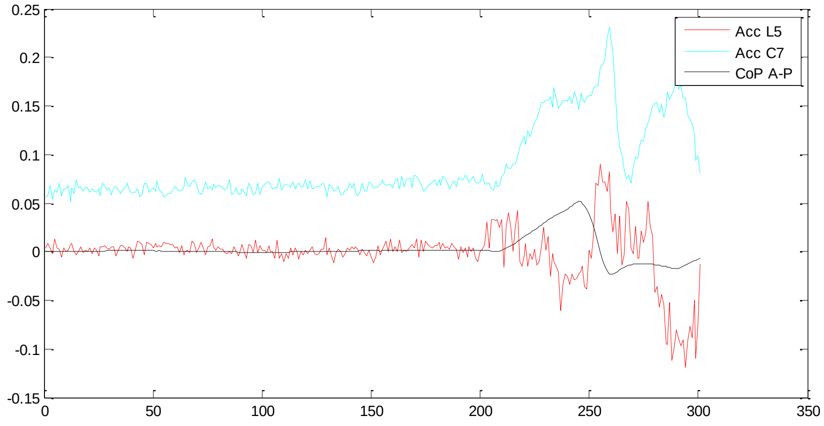


Fig. 5.9.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

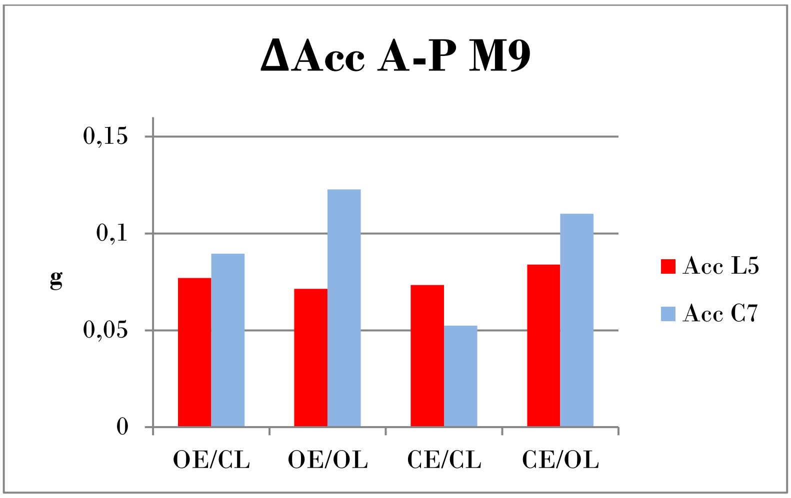


Fig. 5.9.10. Average A-P peak acceleration variation sorted by initial configuration

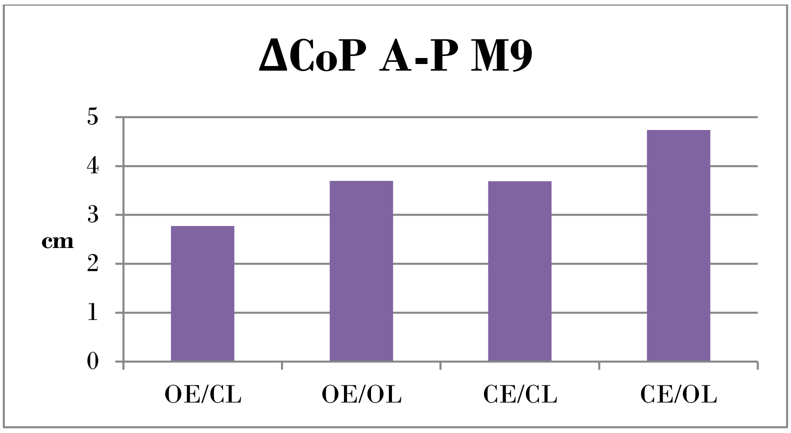


Fig. 5.9.11. Average peak A-P CoP displacement sorted by initial configuratio

5.10.- Turning step to the left (M10)

5.10.1.- Standard deviation

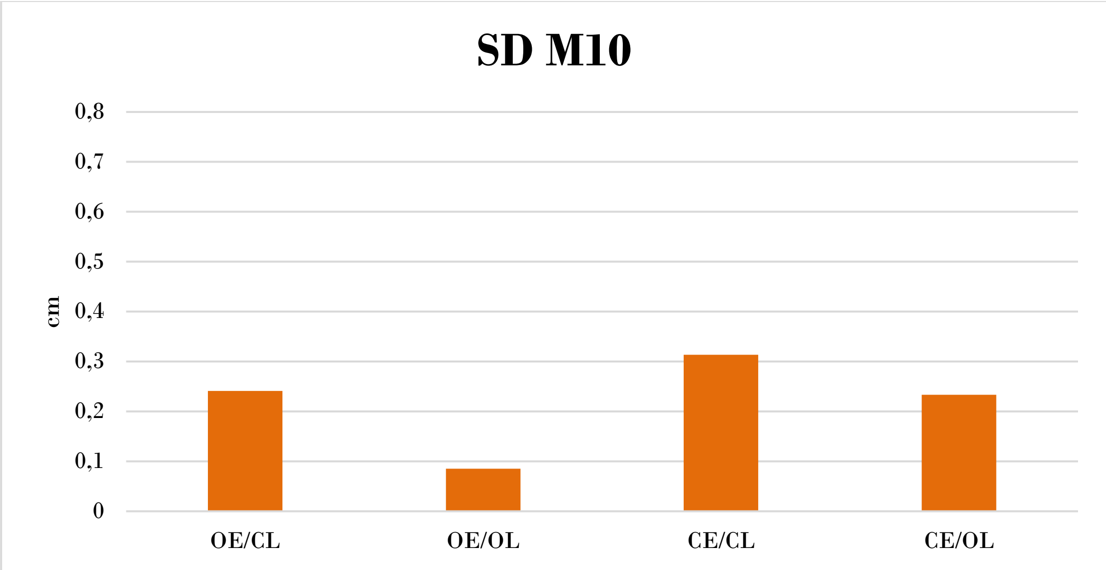


Fig. 5.10.1 Average standard deviation sorted by initial configuration

5.10.2.- Time to peak

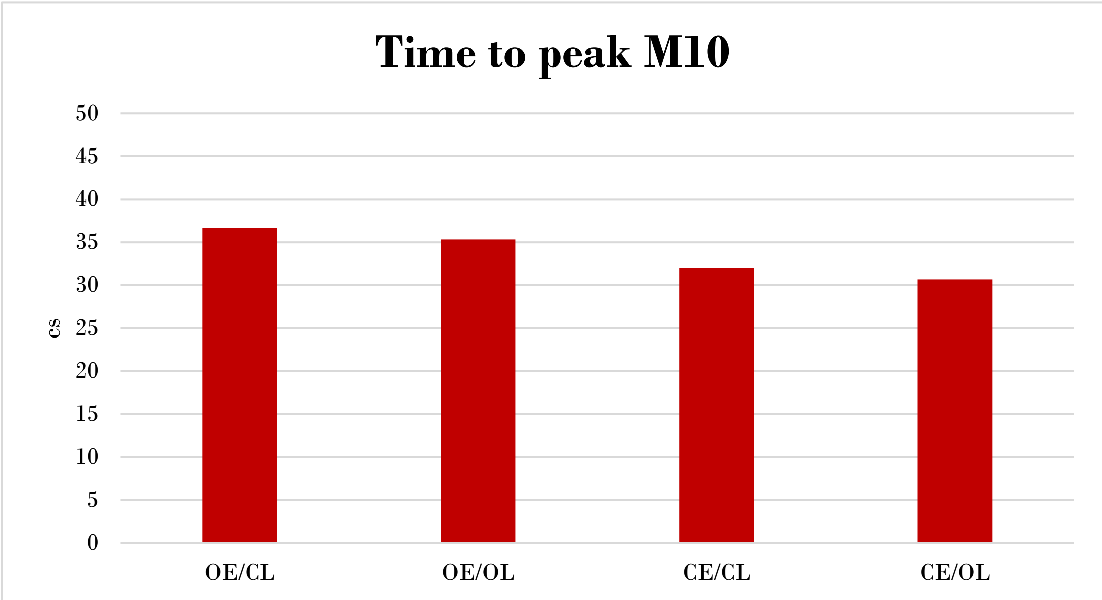


Fig. 5.10.2 Average time to peak sorted by initial configuration

5.10.3.- Force and pressure

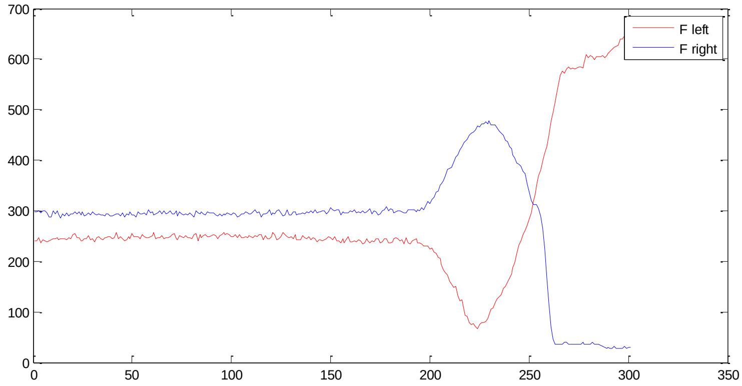


Fig. 5.10.3 Forces (N) on a representative subject before, during and after APA's. Time in cs

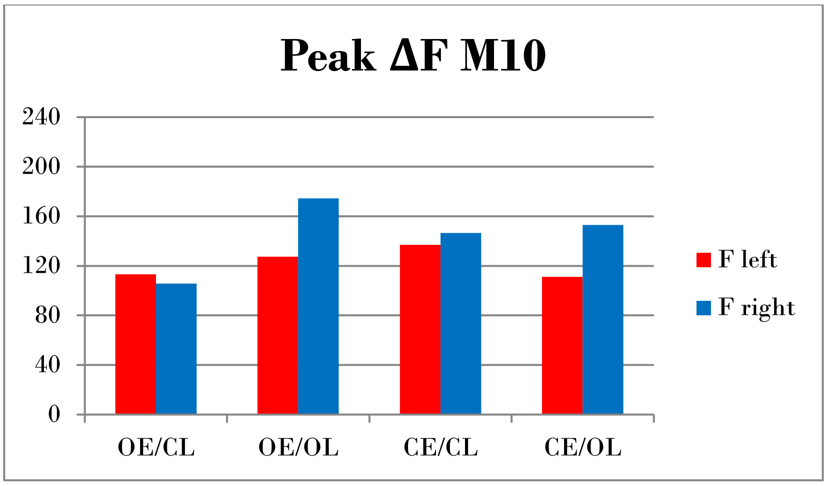


Fig. 5.10.4. Average peak force variation sorted by initial configuration

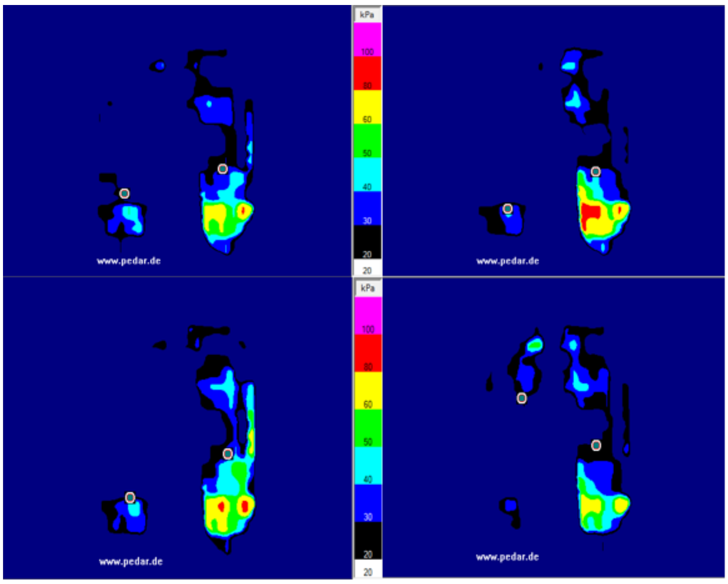


Fig. 5.10.5. Pressure distribution on the feet in the peak M-L CoP displacement moment

5.10.4.- Acceleration and CoP displacement in the medio-lateral direction

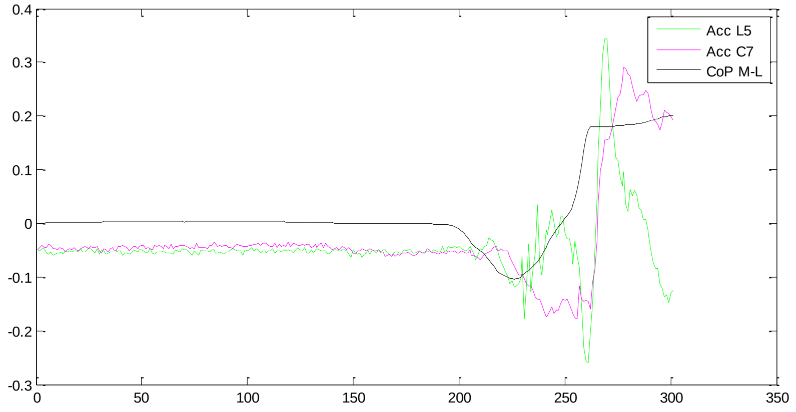


Fig. 5.10.6. M-L accelerations (g) and CoP M-L displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

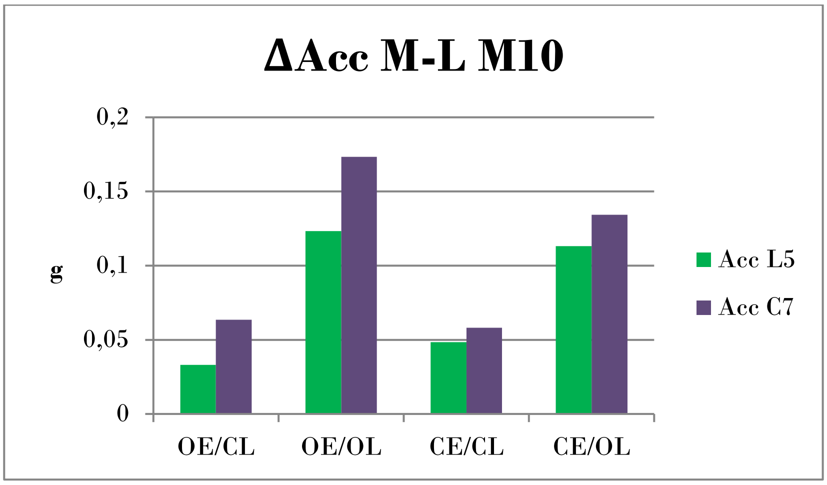


Fig. 5.10.7. Average M-L acceleration variation sorted by initial configuration

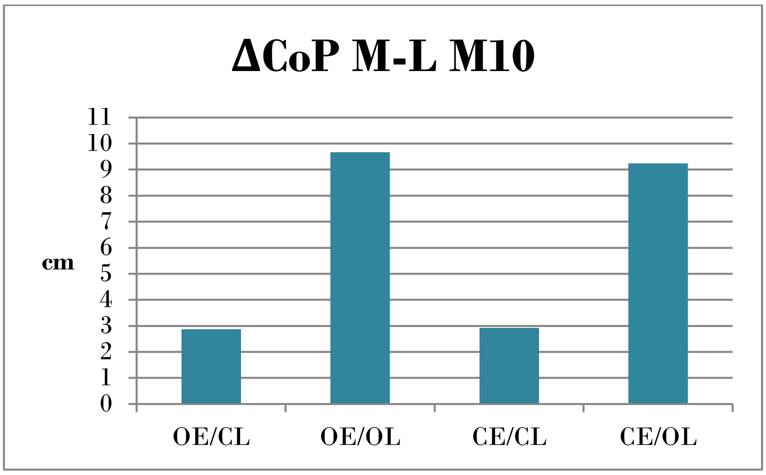


Fig. 5.10.8. Average M-L CoP displacement sorted by initial configuration

5.10.5.- Acceleration and CoP displacement in the antero-posterior direction

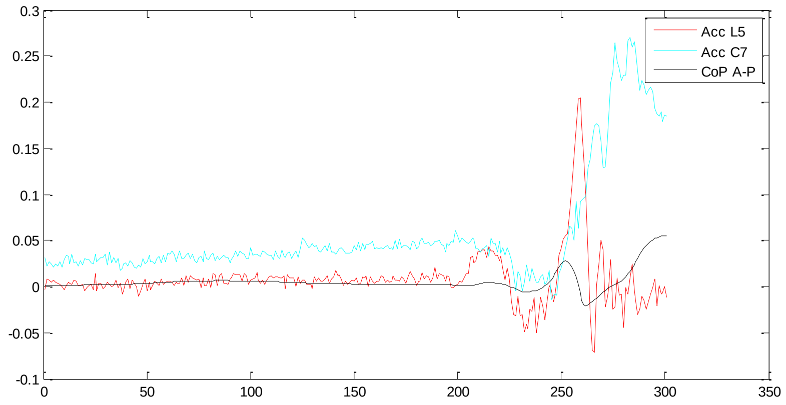


Fig. 5.10.9. A-P accelerations (g) and CoP A-P displacement (m) of a representative subject with OE/OL configuration before, during and after APA's. Time in cs

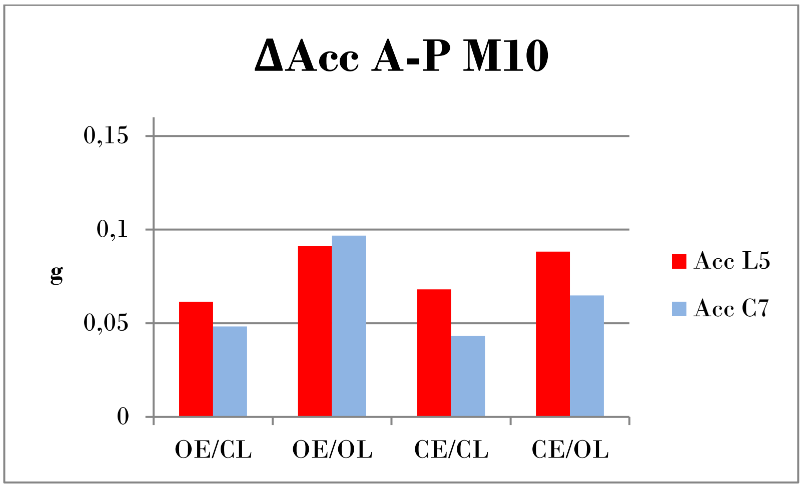


Fig. 5.10.10 Average A-P peak acceleration variation sorted by initial configuration

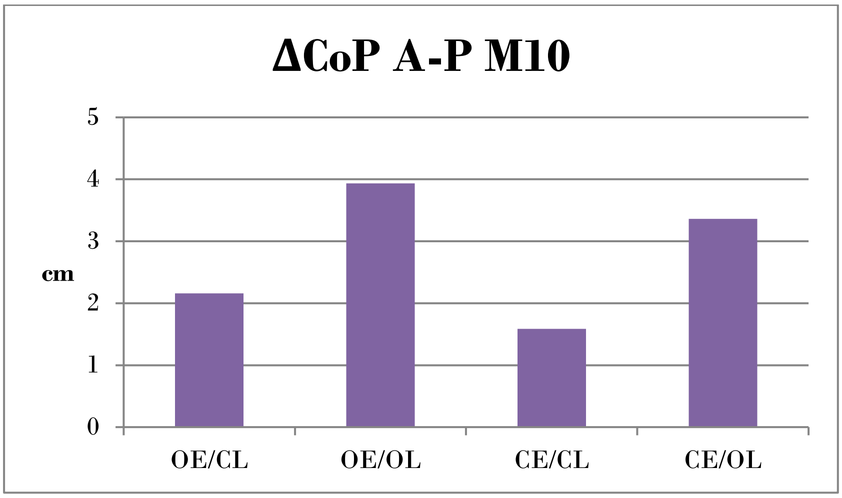


Fig. 5.10.11 Average peak A-P CoP displacement sorted by initial configuration

6.- CONCLUSIONS

6.1.- The accuracy of the APA's detecting method based on standard deviation depends on the initial configuration

The average standard deviation of the medio-lateral CoP position during all the pre-movement waiting phases was calculated. The results sorted by initial configuration are shown in Figure 6.1.1.

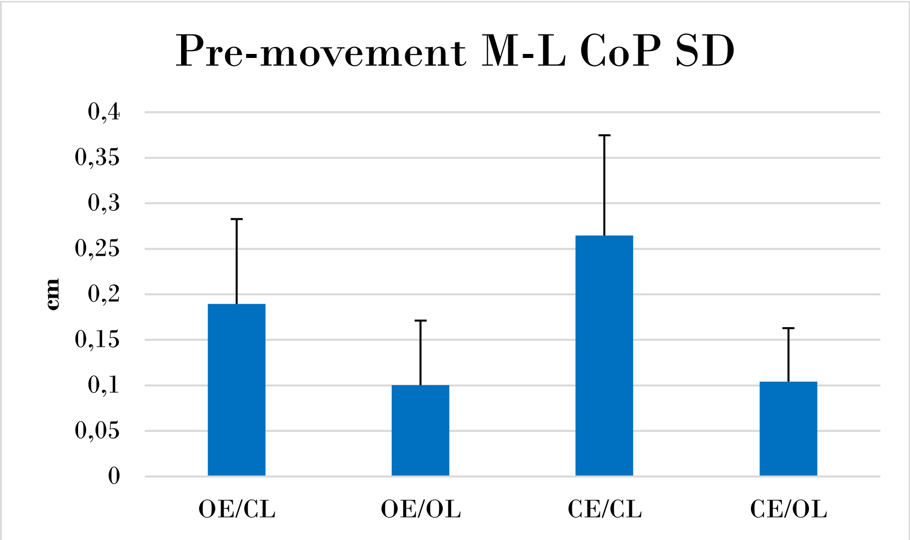


Fig. 6.1.1. Total average SD and SD of the values, sorted by initial configuration.

Even if there is a high dispersion in the values, it is seen from the bar chart that the variation of the medio-lateral CoP position depends on the initial configuration. Regarding open or closed legs, closed legs give less stability to the body and therefore the deviation on the M-L CoP is higher. On the other hand, the effect of the visual condition is not obvious. Results are similar and therefore we cannot conclude that the visual condition influences the variation of the M-L CoP in the quiet pre-movement phase.

This variation of the standard deviation depending on the initial configuration may be a problem when using the APA's detection method used in this and other studies [22] [23] [24]. The method sets a threshold value for detecting the beginning of the APA's as 2 times the M-L CoP standard deviation during the pre-movement quiet phase. Depending on the initial configuration this on-set threshold could be much higher/lower and therefore the estimated length of the APA's shorter/longer. An example is shown on Figure 6.1.2.

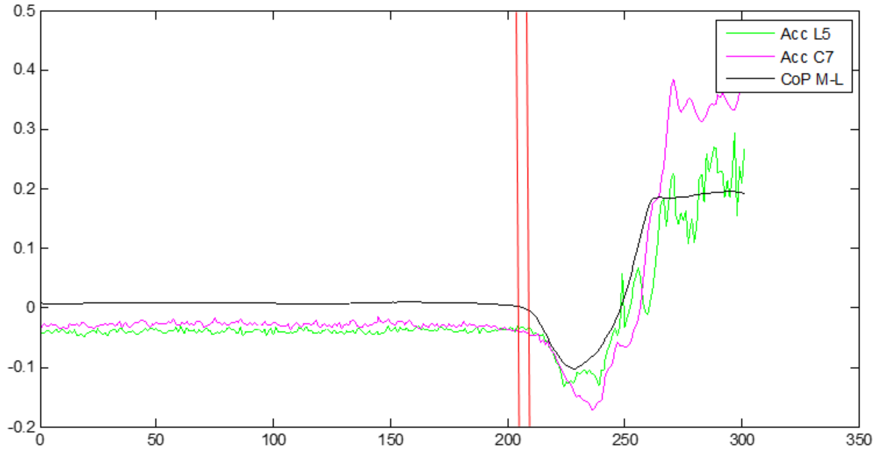


Fig. 6.1.2. Red lines indicate different moments for defining the beginning of the APA's depending on the standard deviation used

6.2.- Peak feet force variation, peak M-L acceleration and maximum M-L CoP displacement vary depending on the initial distance between heels and don't vary with visual conditions

6.2.1.- Time to peak

The average time to peak of all subjects and movements M1 and M3 (right and left short straight step) is shown on Figure 6.2.1, sorted by initial configuration. Both the left and right step were used for this average in order to have a larger amount of data.

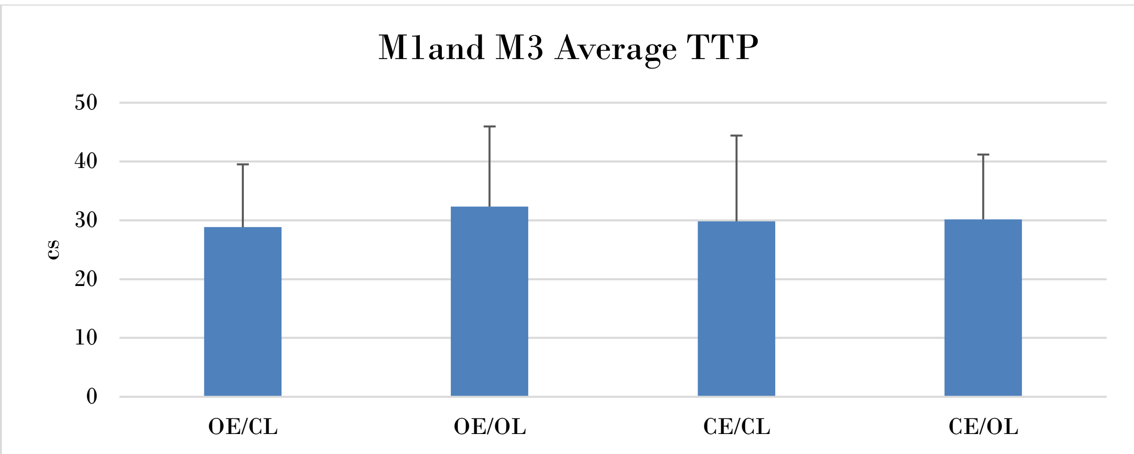


Fig. 6.2.1. Average TTP and SD, sorted by initial configuration

Comparing the first (OE/CL) with the second column (OE/OL), and the third (CE/CL) with the fourth (CE/OL) column, it is not possible to easily appreciate that the initial position of the legs (and hence feet distance) influences the time to peak. In addition, the dispersion of the data is too high to conclude that the initial heel distance influences the time to peak.

Regarding the visual condition influence, the first (OE/CL) with the third (CE/CL) column and the second (OE/OL) with the fourth (CE/OL) column should be compared. Again, the variations in the time to peak are too small to conclude that the visual conditions influence the time to peak.

6.2.2.- Peak feet force variation

The average peak feet force variation of all the movements and subjects is shown on Figure 6.2.2, sorted by initial configuration.

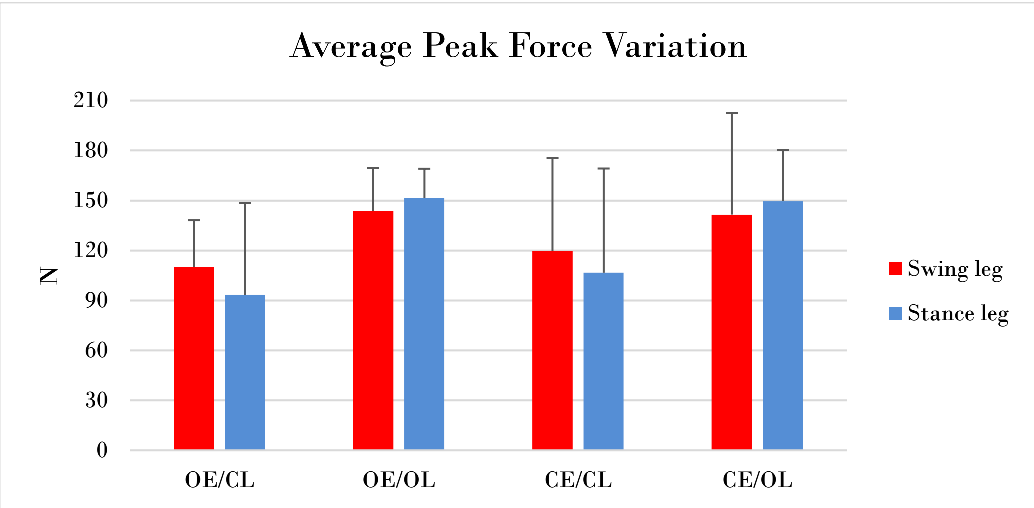


Fig. 6.2.2. Average peak force and SD, sorted by initial configuration

Comparing the first (OE/CL) with the second columns (OE/OL), and the third (CE/CL) with the fourth (CE/OL) columns, it is seen that the initial position of the legs (and hence feet distance) influences the peak force variation. With the open eyes configurations (OE/CL and OE/OL), closed legs decrease the peak force variation with respect to the open legs configuration. With the closed eyes configurations (CE/CL and CE/OL), closed legs decrease the peak force variation with respect to the open legs configuration as well. Therefore we can conclude that the initial heel distance influences the peak feet force variation. Bigger distance means higher peak feet force variations.

Regarding the visual condition influence, the first (OE/CL) with the third (CE/CL) column and the second (OE/OL) with the fourth (CE/OL) column should be compared. With the closed legs configurations (OE/CL and CE/CL), closed eyes barely increase the peak force variation with respect to open eyes configuration. With the open legs configurations (OE/OL and CE/OL), closed eyes have almost the same peak force variation than the open eyes configuration. Therefore we cannot conclude that the visual conditions influence the peak force variation.

6.2.3.- Peak M-L acceleration

The average peak M-L acceleration (in both accelerometers) of all subjects and movements M1 and M3 (right and left short straight step) is shown on Figure 6.2.3, sorted by initial configuration. For the calculations the data of the L5 accelerometer were used.

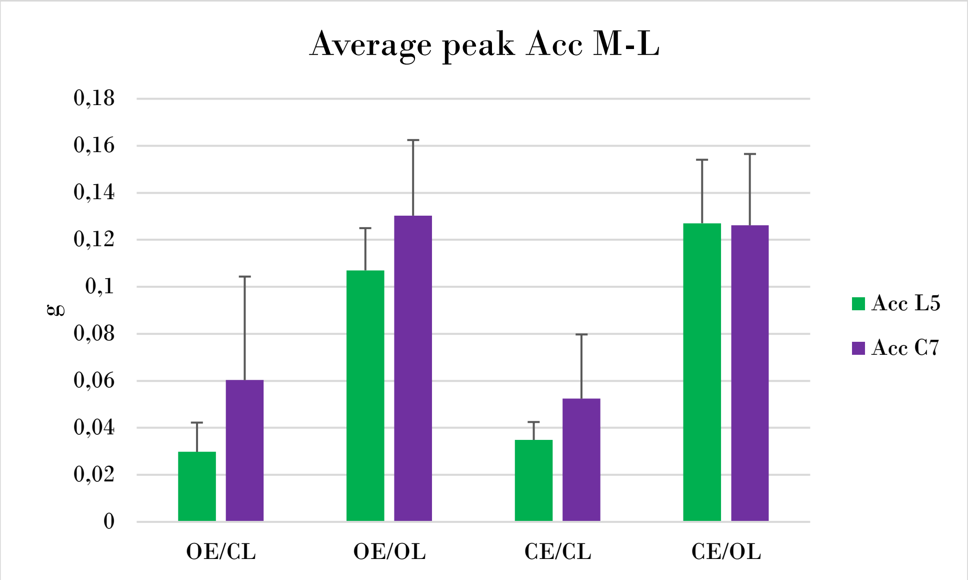


Fig. 6.2.3 Average peak M-L acceleration and SD, sorted by configuration

Comparing the first (OE/CL) with the second column (OE/OL), and the third (CE/CL) with the fourth (CE/OL) column, it is seen that the initial position of the legs (and hence feet distance) influences the peak M-L acceleration. With the open eyes configurations (OE/CL and OE/OL), closed legs decrease by 72% the peak M-L acceleration with respect to the open legs configuration. With the closed eyes configurations (CE/CL and CE/OL), closed legs decrease by 73% the peak M-L acceleration with respect to the open legs configuration. Therefore we can conclude that the initial heel distance influences the peak M-L acceleration. Bigger distance means higher peak M-L acceleration.

Regarding the visual condition influence, the first (OE/CL) with the third (CE/CL) column and the second (OE/OL) with the fourth (CE/OL) column should be compared. With the closed legs configurations (OE/CL and CE/CL), closed eyes increase by 17% the peak M-L acceleration with respect to open eyes configuration. With the open legs configurations (OE/OL and CE/OL), closed eyes increase by 18% the peak M-L acceleration with respect to the open eyes configuration. It seems that the absence of visual information increases the M-L acceleration. However, since the dispersion of the data is high, these variations in the peak M-L acceleration are not enough to conclude that the visual conditions influence the peak M-L acceleration.

6.2.4.- Maximum M-L CoP displacement

The average maximum M-L CoP displacement of all subjects and movements M1 and M3 (right and left short straight step) is shown on Figure 6.2.4, sorted by initial configuration.

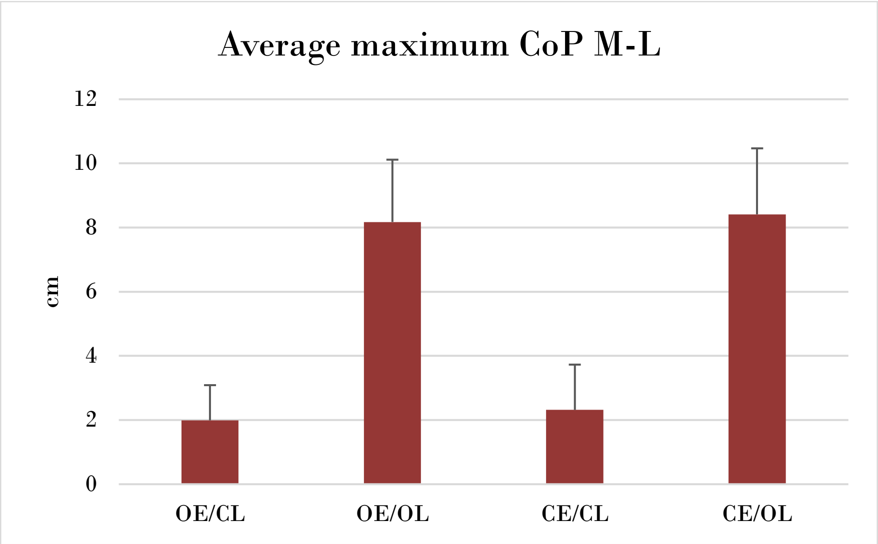


Fig. 6.2.4. Average maximum M-L CoP displacement and SD, sorted by configuration

Comparing the first (OE/CL) with the second column (OE/OL), and the third (CE/CL) with the fourth (CE/OL) column, it is seen that the initial position of the legs (and hence feet distance) influences the maximum M-L CoP displacement. With the open eyes configurations (OE/CL and OE/OL), closed legs decrease by 76% the maximum M-L CoP displacement with respect to the open legs configuration. With the closed eyes configurations (CE/CL and CE/OL), closed legs decrease by 73% the maximum M-L CoP displacement with respect to the open legs configuration. Therefore we can conclude that the initial heel distance influences the maximum M-L CoP displacement. Longer distance means higher maximum M-L CoP displacement.

Regarding the visual condition influence, the first (OE/CL) with the third (CE/CL) column and the second (OE/OL) with the fourth (CE/OL) column should be compared. With the closed legs configurations (OE/CL and CE/CL), closed eyes increase by 16% the maximum M-L CoP displacement with respect to open eyes configuration. With the open legs configurations (OE/OL and CE/OL), closed eyes increases by 3% the maximum M-L CoP displacement with respect to the open eyes configuration. It seems that the absence of visual information increases the maximum M-L CoP displacement. However, these variations in the maximum M-L CoP displacement are too small to conclude that the visual conditions influence the maximum M-L CoP displacement.

6.2.5.- Peak A-P acceleration and maximum A-P CoP displacement

The average peak A-P acceleration and average maximum A-P CoP displacement of all subjects and movements M1 and M3 (right and left short straight step) are shown on Figure 6.2.5 and Figure 6.2.6, sorted by initial configuration.

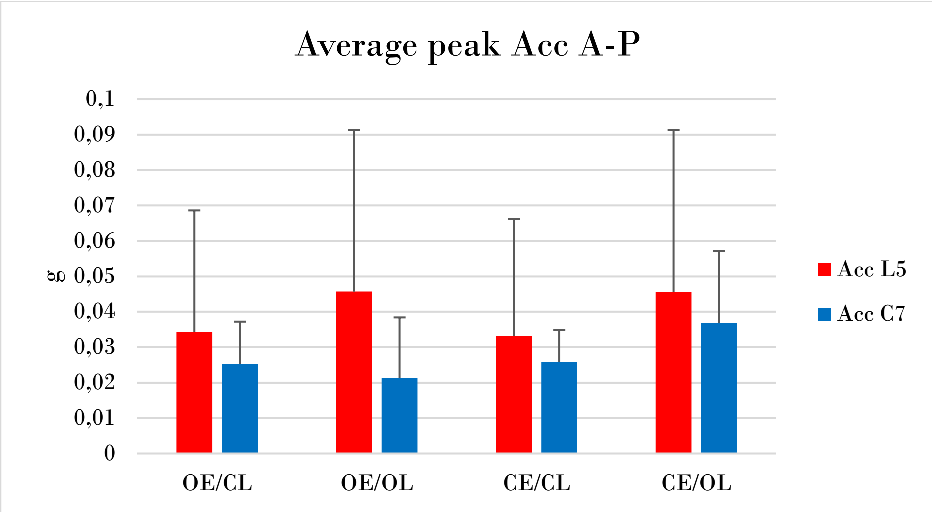


Fig. 6.2.5 Average peak A-P acceleration and SD, sorted by configuration

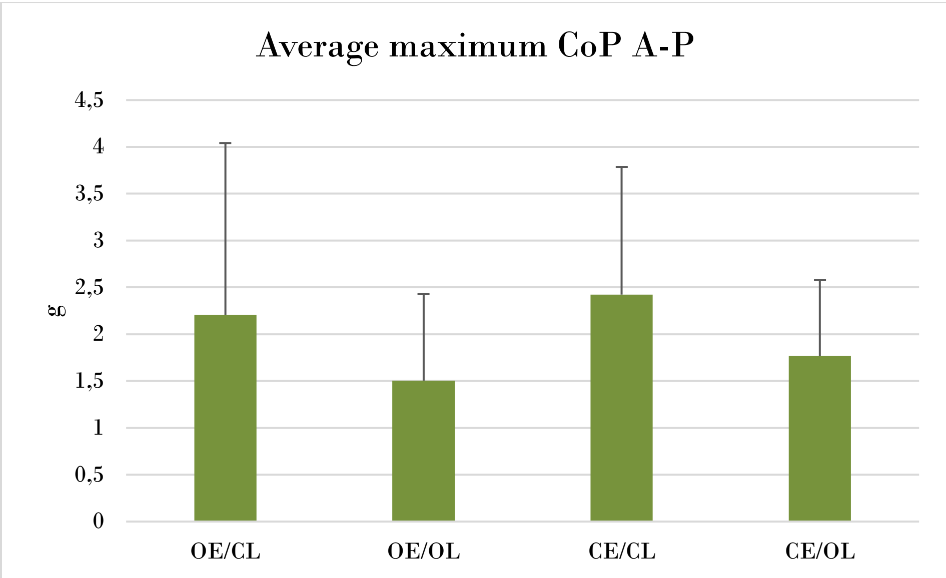


Fig. 6.2.6. Average maximum A-P CoP displacement and SD, sorted by initial configuration

Comparing both the heel distance influence (the first OE/CL with the second OE/OL column and the third CE/CL with the fourth CE/OL column) and the visual conditions influence (the first OE/CL with the third CE/CL column and the second OE/OL with fourth CE/OL column) and taking into account the high dispersion of the data, it is not possible to make any reliable conclusion.

6.2.6.- Summary

The Table 6.2.1 summarizes the conclusions explained in this part.

	TTP	Peak force	Acc L5 M-L	Acc C7 M-L	CoP M-L	Acc L5 A-P	Acc C7 A-P	CoP A-P
Influenced by closed legs	Not clear	Yes	Yes	Yes	Yes	Not clear	Not clear	Not clear
Influenced by closed eyes	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear	Not clear

Table 6.2.1. Influence of the initial configurations on the parameters

6.3.- Long steps have a higher acceleration peak and maximum CoP displacement than short steps in both M-L and A-P directions

The average acceleration peak and maximum CoP displacement were compared for both short and long steps. The data obtained on the right and left step was used in order to have more results and therefore a more reliable conclusion. The information of the L5 accelerometer was used for this comparison, since it is more reliable than the C7 one [22]. The results obtained and explained below agree with the conclusion obtained in [36].

6.3.1.- Medio-lateral direction

It is seen from Figure 6.3.1. that in 6 out of the 8 different cases (4 different configurations and right/left step) the M-L acceleration peak was higher when performing the long step. We can conclude then that the M-L acceleration peak reaches higher values when we are required to do a longer step.

In addition, it is seen from Figure 6.3.2. that in 6 out of the 8 different cases (4 different configurations and right/left step) the maximum M-L CoP displacement was higher when performing the long step. We can conclude then that the maximum M-L CoP displacement reaches higher values when we are required to do a longer step.

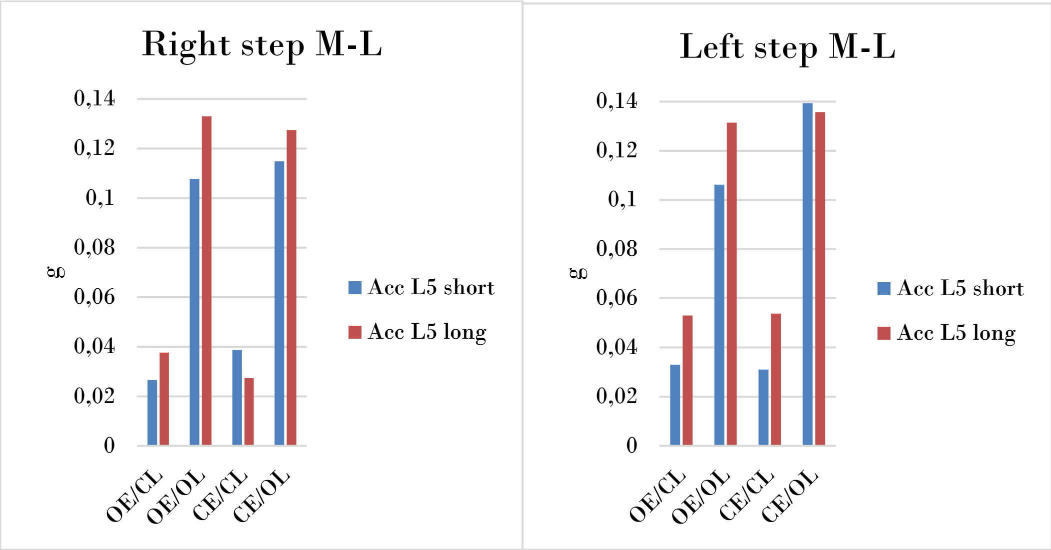


Fig. 6.3.1. Long and short step peak M-L acceleration comparison

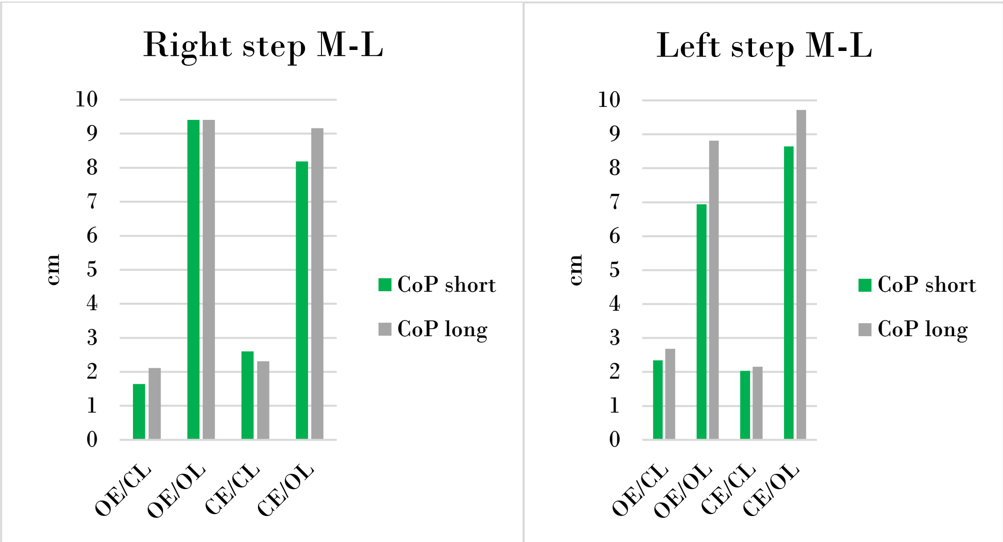


Fig. 6.3.2. Long and short step maximum M-L CoP displacement

6.3.2.- Antero-posterior direction

The same procedure as in the medio-lateral direction has been followed for the antero-posterior direction.

Figure 6.3.3. shows that in 8 out of the 8 different cases (4 different configurations and right/left step) the A-P acceleration peak was higher when performing the long step. We can conclude then that the A-P acceleration peak reaches higher values when we are required to do a longer step.

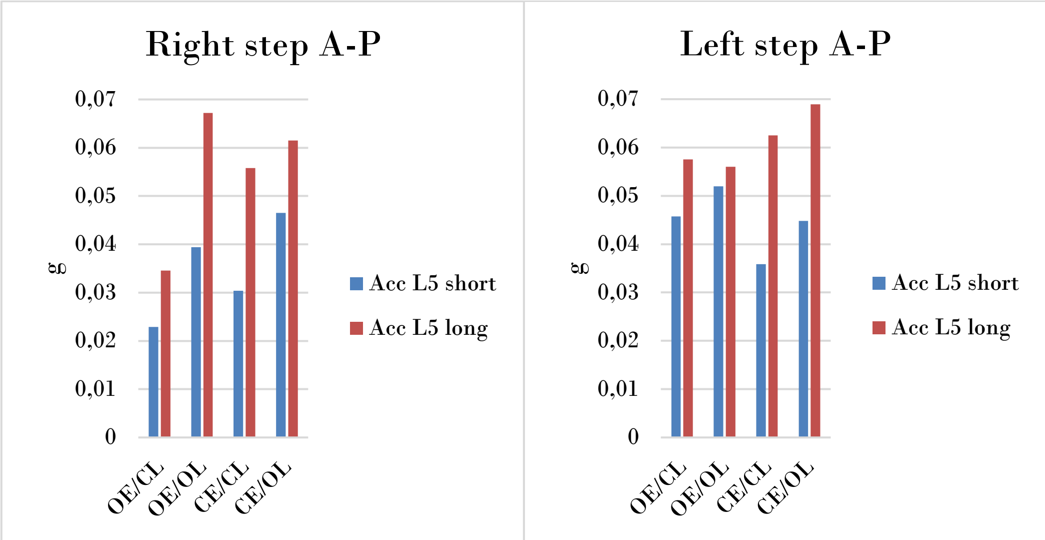


Fig. 6.3.3. Long and short step peak A-P acceleration comparison

At the same time, Figure 6.3.4. shows that again in 8 out of the 8 different cases (4 different configurations and right/left step) the maximum A-P CoP displacement was higher when performing the long step. We can conclude then that the maximum A-P CoP displacement reaches higher values when we are required to do a longer step.

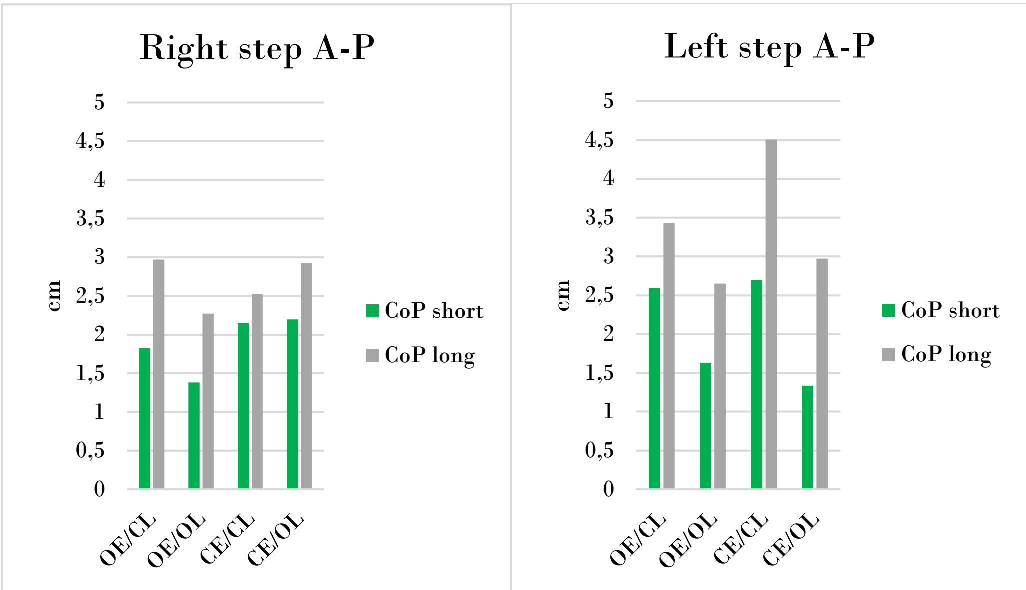


Fig. 6.3.4. Long and short step maximum A-P CoP displacement

Previous results are consistent with the commonly accepted biomechanical interpretation of the APA's and their direct link with the subsequent movement. In particular, the larger the movement the higher are the APA peaks on both CoP and accelerometers in order to better prepare the body to a larger potential destabilization.

6.4.- Turn steps have a higher acceleration peak and maximum CoP displacement than straight steps in both M-L and A-P directions

The average acceleration peak and maximum CoP displacement were compared for both turn and straight steps. The data obtained on the right and left step have been used in order to have more results and therefore a more reliable conclusion. The information of the L5 accelerometer was used for this comparison.

6.4.1.- Medio-lateral direction

It is seen from Figure 6.4.1. that in 6 out of the 8 different cases (4 different configurations and right/left step) the M-L acceleration peak was higher when performing the turn step. We can conclude then that the M-L acceleration peak reaches higher values when we are required to do a turn step instead of a straight step.

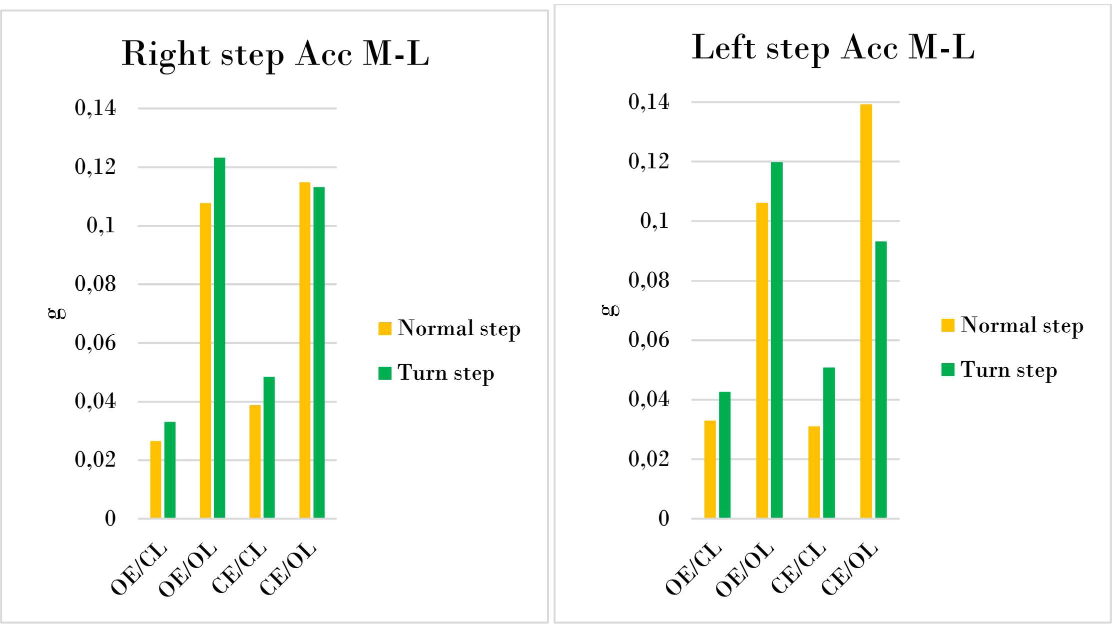


Fig. 6.4.1. Straight and turn step peak M-L acceleration comparison

In addition, it is seen from Figure 6.4.2. that in 8 out of the 8 different cases (4 different configurations and right/left step) the maximum M-L CoP displacement was higher when performing the turn step. We can conclude then that the maximum M-L CoP displacement reaches higher values when we are required to do a turn step.

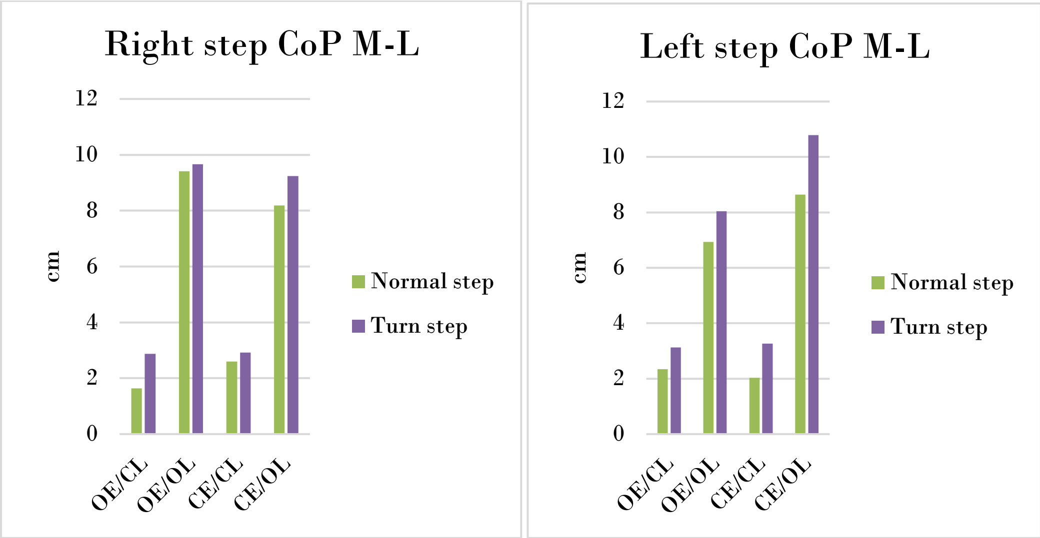


Fig. 6.4.2. Straight and turn step maximum M-L CoP displacement

6.4.2.- Antero-posterior direction

The same procedure as in the medio-lateral direction has been followed for the antero-posterior direction.

Figure 6.4.3. shows that in 8 out of the 8 different cases (4 different configurations and right/left step) the A-P acceleration peak was higher when performing the turn step. We can conclude then that the A-P acceleration peak reaches higher values when we are required to do a turning step.

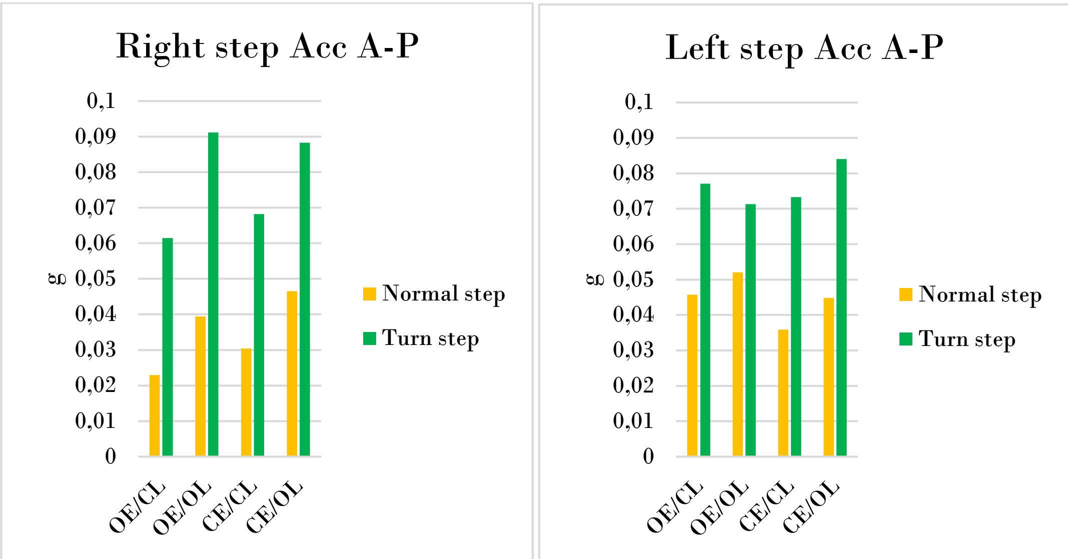


Fig. 6.4.3. Straight and turn step peak A-P acceleration comparison

At the same time, Figure 6.4.4. shows that again in 8 out of the 8 different cases (4 different configurations and right/left step) the maximum A-P CoP displacement was higher when performing the turn step. We can conclude then that the maximum A-P CoP displacement reaches higher values when we are required to do a turn step.

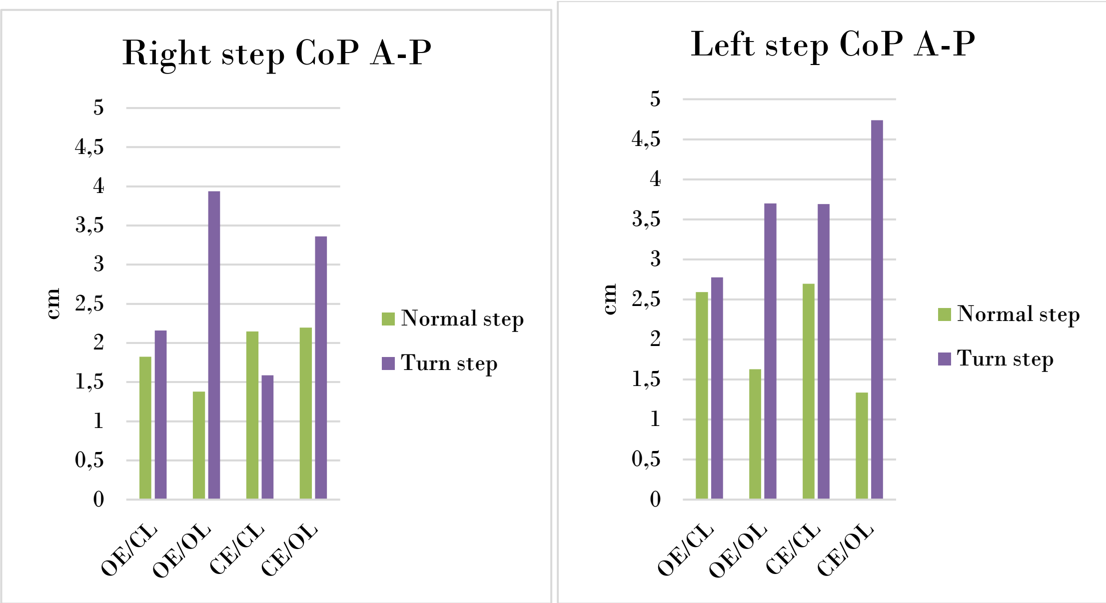


Fig. 6.4.4. Straight and turn step maximum A-P CoP displacement

6.5.- Back steps have a higher acceleration peak and maximum CoP displacement than forward steps in the A-P direction

The average acceleration peak and maximum CoP displacement were compared for both back and forward steps. The data obtained on the right and left step were used in order to have more results and therefore a more reliable conclusion. The information of the L5 accelerometer was used for this comparison.

6.5.1.- Medio-lateral direction

Figure 6.5.1 show that there is not in all the 8 cases (4 configurations and right/left step) a clear higher acceleration on the forward or the back step. In some cases the acceleration is higher for the forward and in others for the back step.

The results of the maximum M-L CoP (Figure 6.5.2.). displacement neither show a clear tendency, being in some cases higher for the forward step and in other for the back step.

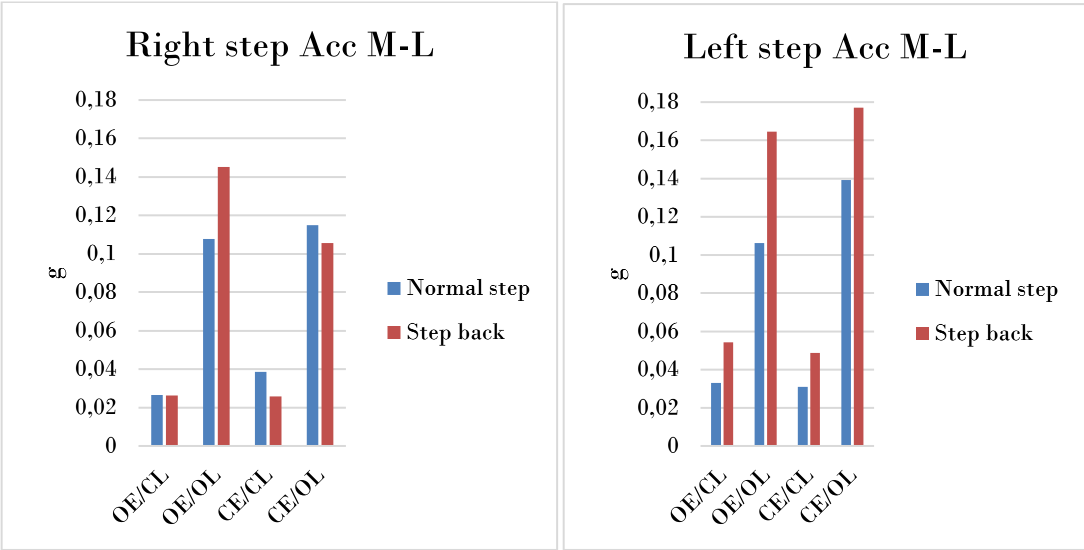


Fig. 6.5.1. Forward and back step peak M-L acceleration comparison

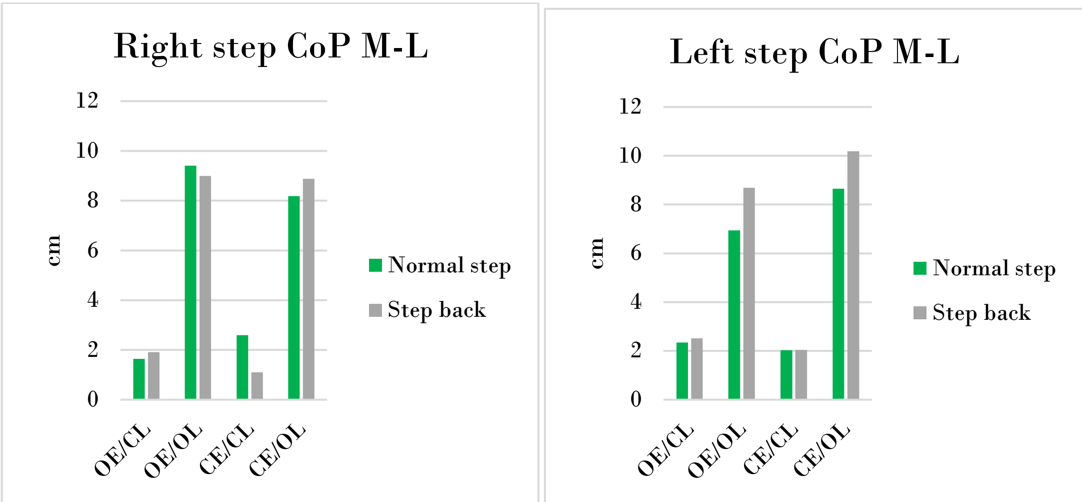


Fig. 6.5.2. Forward and back step maximum M-L CoP displacement

To sum up, it is not clear than the step back has a higher or lower M-L acceleration and CoP displacement than the forward step.

6.5.2.- Antero-posterior direction

The same procedure as in the medio-lateral direction has been followed for the antero-posterior direction.

Figure 6.5.3. shows that in 8 out of the 8 different cases (4 different configurations and right/left step) the A-P acceleration peak was higher when performing the back step. We can conclude then that the A-P acceleration peak reaches higher values when we are required to do a back step (comparing with the forward step).

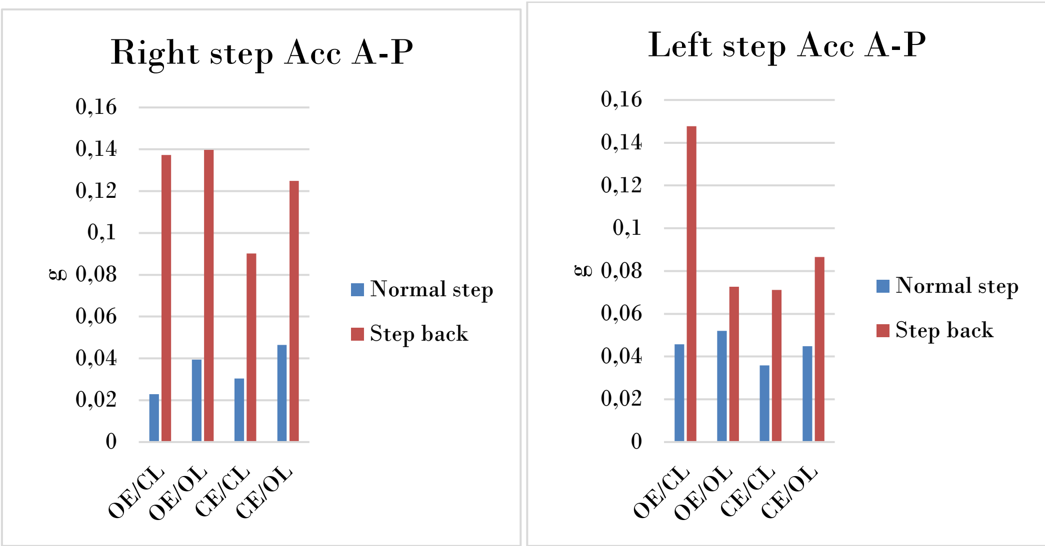


Fig. 6.5.3. Forward and back step peak A-P acceleration comparison

At the same time, Figure 6.5.4. shows that again in 8 out of the 8 different cases (4 different configurations and right/left step) the maximum A-P CoP displacement was higher when performing the back step. We can conclude then that the maximum A-P CoP displacement reaches higher values when we are required to do a back step (comparing with the forward step).

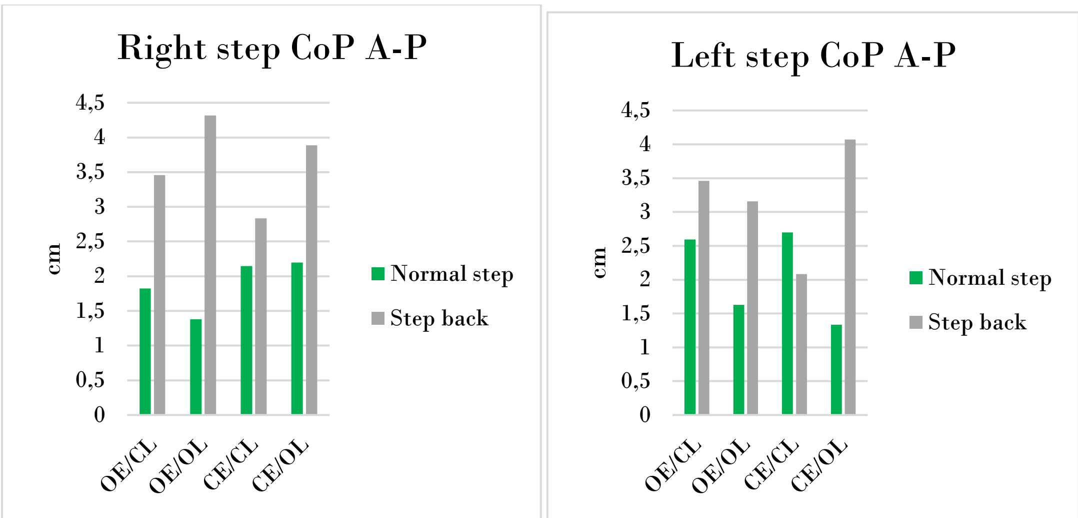


Fig. 6.5.4. Forward and back step maximum A-P CoP displacement

The reason of these higher values in both A-P acceleration and CoP displacement in the step back is that the body has more available feet surface to vary the CoP position during it. When we want to perform a step forward, during the APA's, the CoP moves back and forward. On the other hand, when we want to perform a step back, during the APA's, the CoP moves forward and back. The available feet surface we have to perform the forward step APA's is smaller than for the step back (Fig. 6.5.5).

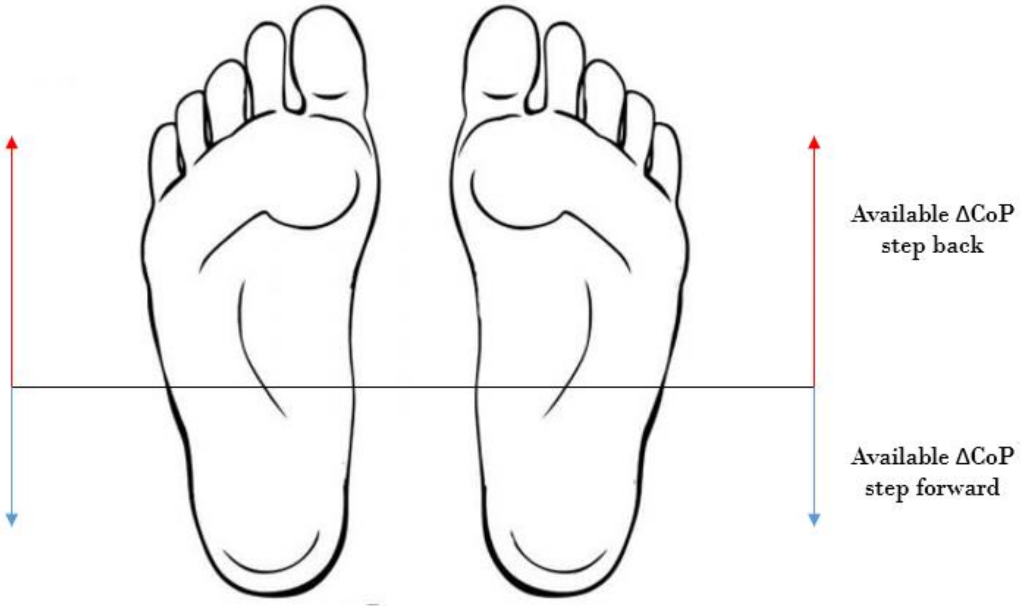


Fig. 6.5.5. Available surface for CoP displacement during APA's in step back/forward

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Hasta la próxima.