EFFECT OF PREGNANCY-INDUCED MASS GAIN AND FOOTWEAR ON POSTURAL STABILITY

By

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EFFECT OF PREGNANCY-INDUCED MASS GAIN AND FOOTWEAR ON POSTURAL STABILITY

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Abstract:

Pregnancy induces tremendous changes in the body, which increases the risk of falling. Falls are rarely as costly as when they happen during pregnancy, leading to tremendous healthcare, emotional, and societal costs. More than one in four women (27%) fall at least once during pregnancy. Despite overwhelming statistics, there is a dearth of interventions to minimize the risk of falling amongst pregnant women. Our goal was to quantify the effect of pregnancy-induced mass gain and footwear on postural stability throughout pregnancy, as a first step towards a deeper understanding of pregnancy-specific optimal postural strategies. Our main hypothesis was that both footwear and pregnancy mass affect postural stability.

Postural stability was assessed on ten young healthy non-pregnant women and pregnancy was simulated by adding localized weights. Measurements were performed during four sessions (not pregnant, first, second, and third trimesters) wearing five types of footwear in randomized order: flats, sports, low heels, and sports and low heels with ankle brace. The center of pressure (COP) was determined for each instant in time and 22 COP-based postural stability indices (15 temporal and 7 spectral) were computed. The effect of pregnancy-induced mass gain and footwear on each index was assessed using repeated measures ANOVA.

Pregnancy-induced mass gain and footwear have an influence on the postural stability of healthy young female subjects, independently of all other pregnancy-induced physical, hormonal, and psychological changes. Results demonstrated a decrease in mediolateral postural stability with mass gain and footwear such as heels. Ankle braces worn with sport shoes seem to increase postural stability. The decrease in postural stability is detected by a decrease in postural sway, due to a tighter postural adjustment and a rigidification of the posture. This rigidification of the posture results from muscle contraction, which would lead to muscle fatigue if performed continuously during a pregnancy.

This study paves the way for a deeper understanding of postural strategies adopted by pregnant women while wearing different footwear, and thus for the development of efficient fall-avoidance strategies.

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CHAPTER I

INTRODUCTION AND BACKGROUND

1.1 Background

1.1.1 Postural stability

Definition

Postural stability is defined as the ability to maintain an upright position [Rogers2013]. Postural stability is directly correlated with the performance of the postural control system in responding to external perturbations, and is usually evaluated with the measurement of postural sway [Maki1986].

The postural control system integrates information from various body systems, such as the visual, vestibular, and proprioceptive systems, to maintain an upright posture and avoid falling. The working of these systems has a prominent impact on postural control. If these systems' working is impaired or deteriorated due to any medical condition, like old age or neurological disease, then the postural control system compensates by varying relative weighting factors of the inputs to maintain postural balance [Nashner1971, Diener1988, Cohen1989, Keshner1989, Manchester1989]. Thus, a variety of health conditions related to age and neurological diseases have been diagnosed using postural stability assessments [Era1985, Prieto1993, Chaudhry2005].

Several techniques are used to quantify postural sway, such as measuring the movement of the center of pressure (CoP) under the feet, motion of body segments or joints, joints moments, and EMG activity [Maki1986]. The most common method is to measure the position of the CoP through time with a force platform or a pressure mat. The CoP corresponds to the acting point of the resultant force vector of the ground reaction force [Cavanagh1978]. The CoP and the vertical projection of the center of mass overlap in static conditions only and should not be mistaken to be the same in dynamic conditions. Apart from the CoP displacement, many other measures computed from the output signal from the force platform have been implemented to assess postural stability [Wikstrom2005].

Universal and subject-specific postural stability indices

The complex temporal motion of the CoP in the anterior-posterior (AP) and medio-lateral (ML) directions is commonly recorded as a series of coordinates in the AP-ML plane through time. This CoP time series cannot be modeled using a simple mathematical relation but rather using a two-dimensional stochastic process [Carroll1993, Collins1994, Loughlin1996]. The CoP time series can be characterized by numerous scalar-valued indices, such as sway size, mean sway velocity, or the total length of sway to name a few [Yamamoto2015]. These indices are often categorized based on their computation domain, *i.e.* time-domain or frequency-domain [Prieto1993]. The *time-domain indices* include the CoP mean velocity and the CoP total path for example, whereas the *frequency-domain indices* refer to the indices derived from the CoP power spectral density.

To understand postural stability, a more valuable categorization divides indices into *subject-specific* and *universal* characteristics of postural sway [Yamamoto2015]. In a comprehensive study comparing measures of postural stability [Yamamoto2015], 22 out of 73 computed indices have been categorized as either universal or subject-specific indices. The remaining indices could not be categorized for lack of statistical significance. The subject-specific indices exhibit variability among subjects, with almost no trial-to-trial variations in the values among the same individuals. Subject-specific indices are associated with the fast and very-fast oscillatory components of the sway, in the frequency range above 5 Hz [Yamamoto2015], and correlate with individual body characteristics rather than neural control [Kiemel2006]. Postural stability indices that are invariant across healthy young subjects and independent of body parameters are referred to as universal indices [Yamamoto2015]. These universal indices quantify the origin of postural fluctuations, *i.e.* the control mechanisms of the neural system [Yamamoto2015]. They are associated with the slow components of sway in the frequency range of 0.1 to 0.5 Hz [Yamamoto2015]. These slow components have been pointed out as the major contributors of postural instability during upright standing [Yamamoto2015].

In our study, we aimed at quantifying the effects of footwear and mass gain during pregnancy by computing these 22 identified indices. They will be described in details in Chapter 2.

Risk of falling

A fall is an unintentional event that results in a person coming to rest on the ground [Kellogg1987]. The complete fall event can be described in three phases. The first phase is the initiation, usually due to the displacement of the center of mass outside the base of support. The base of support refers to the area around the outside edge of the contact between feet and floor. The second phase involves the failure of various body systems to detect and compensate for the displacement of the center of mass. The third phase corresponds to the impact exerted by the ground in contact with the body, which results in forces being transmitted to the tissues and organs. Although technically not part of the fall event, the final phase is concerned with the consequences of the fall, mainly psychological and medical conditions. Attempting to prevent falls starts with focusing on factors related to each of these phases.

The risk of falling quantifies the likelihood that a person will fall [Tinetti1998]. The risk of falling will obviously increase with a decrease in postural stability. Generally, *intrinsic factors* determine an individual's risk of falling by accounting for the variations in musculoskeletal and sensory systems [Perell2001]. *External factors* like fatigue, training, medication, and mental health status including fear of falling, also influence the risk of falling [Perell2001]. The best approach to measure the risk of falling of an individual would be to quantify each factor. However, the quantification of some factors or their combined effects is difficult [Kang2006]. Thus, alternative ways using 'indirect and comprehensive' indices have been proposed and utilized as measures of the risk of falling, highlighting the compensation mechanisms and postural stability strategies exhibited by individuals [Liu2012]. Postural stability indices such as the average velocity of CoP during quiet upright standing account for these indirect and comprehensive factors.

1.1.2 Effect of pregnancy on postural stability

Daily activities or work-related tasks that are usually easy to perform become tedious and problematic when pregnant. One study showed that 26.8% of pregnant women fall at least once during their pregnancy [Dunning2003], which is close to the fall rate of elderly women (29%) [O'Loughlin1993]. Also, 27% of women who fall are pregnant, and more than 10% experience multiple falls [Kuo2007].

These falls have negative consequences. Nearly 24% of maternal injury hospitalizations result from falling [Kuo2007]. Falls cause serious injuries including bone fractures, joint and muscle sprains, head injury, rupture of internal organs such as uterus and membranes, internal hemorrhage, and abruptio placentae [Fildes1992]. In the worst case, a fall can lead to maternal death or fetal demise [Fildes1992].

A typical pregnancy lasts for about 40 weeks starting from the day of conceiving until birth. Pregnancy is commonly divided into three trimesters, namely: first trimester (0-13 weeks), second trimester (14-26 weeks), and third trimester (27-40 weeks) [Chislom2017]. Women experience numerous anatomical and physiological changes during their pregnancy, some of which affect the musculoskeletal system. For instance, relaxin hormone, muscle stretching, and interstitial fluid increase during pregnancy, affecting ligament laxity and input of sensory systems [Rasmussen2009].

One of the changes that most affect musculoskeletal health during pregnancy is the local increase of mass. The mass gain during pregnancy results from the fetus mass as well as the increases in amount of blood, volume of the breast, and extracellular fluid [Widen2014]. The increase in mass during pregnancy highly depends on the body mass index (BMI) before pregnancy. The pregnancy-induced mass gain ranges between 12.5

kg and 18 kg for underweight women (BMI < 18.5), between 11.5 kg and 16 kg for "normal" weight women (18.5 < BMI < 25), between 7 kg and 11.5 kg for overweight women (25 < BMI < 30), and between 5 kg and 9 kg for obese women [InstituteofMedicine2009]. The total relative mass gain is approximately 15%-25%, mainly located in the lower trunk and during the second and third trimesters [Jensen1996]. Several adverse maternal effects can arise from gaining too much weight during pregnancy, such as gestational hypertension, gestational diabetes, difficulties during labor, etc [Goldstein2017].

Because the added mass is positioned forward of the pelvic midpoint, the center of mass moves from the center of the pelvis to a point forward and slightly upward. The displacement of the center of mass, the added forward gravitational pull, as well as the change in the inertial properties of the body [Harris2015] lead to posture adjustments, reflected by an increased curvature of the lumbar and cervical spinal regions [Yoo2015], an increased inclination of the trunk [Krkeljas2018], an elevation of the head, and an extension of the knee and ankle joints [Fries1943]. Due to these adjustments, women experience stress on muscles and joints, increased load on vertebrae, higher structural discomfort, etc. Moreover, foot pain arises from the increased loading on plantar tissues [Mitternacht2013, Karadag-Saygi2010].

The postural stability of pregnant women has been quantified by several postural stability indices, *e.g.* the CoP trajectory deviation [Mei2018], the CoP displacement or sway [Danna-Dos-Santos2018], the CoP maximum moving area [Mun2019], and the center of mass (CoM) displacement [Flores2018]. Indices of postural stability computed from experimental measurements on pregnant subjects indicate an increase of the risk of falling during pregnancy [Butler2006, Inanir2014, Ersal2014]. The high risk of falling, or low postural stability, experienced by pregnant women is thought to directly result from the physical changes and posture adjustments.

To overcome this issue of postural instability, pregnant women develop new strategies of postural control. Pregnant women rely more heavily on feedforward or anticipatory mechanisms than on feedback mechanisms, causing subtle changes in postural sway and safer ways to control ML balance [Danna-Dos-Santos2018]. Feedforward mechanisms involve inculcating more repetitive CoP patterns fluctuation in time and thus improving the synchronization between AP and ML sway to improve postural stability [Danna-Dos-Santos2018]. Feedback mechanisms such as stretch reflexes are used as a reaction to disturbances to maintain postural stability [Finley2009]. Under normal circumstances, these two strategies coexist, but the response would change according to internal or environmental conditions [Mohapatra2014, Welch2014].

1.1.3 Effect of footwear on postural stability

Feet are the only body parts that touch the ground while standing or walking. Feet are also an important source of afferent feedback for locomotion and balance [Palluel2008, Priplata2002, Wang2012, Wu2007]. Footwear is used to protect the foot, to ease commuting on foot, to accommodate foot deformities, and to treat musculoskeletal injuries [Barnish2016]. Footwear is designed to give support and stability to the foot, potentially affecting its functionality and proprioception. Thus, footwear has a very important role in improving the well-being of any individual.

Although the primary use of footwear is to protect the foot from the surrounding environment and facilitate propulsion [McPoil1988], footwear is also designed for fashion and aesthetics. In general, women wear three types of footwear:

- Flats, which are analogs to barefoot in terms of height but differ in the material in contact with the foot and the ground.
- Heels, which vary predominantly in the heel height from 1 to 5 inches and have a smaller contact area with the ground.
- Sports shoes, which completely harness the foot providing comfort, a larger contact area with the ground, and negligible heel height.

Footwear can also improve the sensory information received by the foot through the tactile and proprioceptive systems [Alghadir2018]. The cutaneous mechanoreceptors of the foot plantar surface detect a tactile stimulation and inform the central nervous system on plantar pressure distribution [Perry2007, Hijmans2007]. Since balance is impaired if plantar afferent receptors are damaged, stimulation of these receptors via footwear can significantly enhance postural stability [Meyer2004, Maki1999, Arnadottir2000]. Footwear characteristics have been linked to falls in older adults, children, and pregnant women [Barton2009, Dunning2010]. Postural stability decreases in the elder population equipped with poor footwear [Brenton-rule2011]. The use of thin and hard-soled footwear with high collars increased postural stability [Aboutorabi2016]. A study conducted on healthy male participants to assess the postural stability wearing standard shoes and sandals when compared to barefoot has concluded that sandals would decrease the postural stability whereas shoes did not affect stability [Alghadir2018].

Studies have not conclusively assessed the influence of footwear on postural stability, mainly due to the variability is postural stability measures [Federolf2012]. It has been suggested in [Fedorolf2012] that studying postural movements rather than CoP data would be a better way of quantifying postural stability. CoP mean in AP direction in closed-eye conditions, CoP range, and 95% confidence elliptical area have also proven useful measures of postural stability according to footwear [Brenton-Rule2014].

An additional footwear feature influencing postural stability is the presence of ankle support. Ankle support is achieved by stiffening the ankle joint through the shoe or a separate ankle brace. The ankle support provided by ankle boots is equivalent to wearing soft ankle braces, which are primarily used as preventive measures against ankle sprains [Hootman2007, Wilkerson1992, VandenBekerom2012]. Hard ankle braces aim at immobilizing the ankle joint or at severely limiting its range of motion [Ivins2006]. Independently of pregnancy, the effect of ankle braces on postural stability has not been conclusively determined yet [Guskiweicz1996]. In general, ankle braces decrease the shear force on the anterior tibial, constrain the motion of the ankle, improve ankle proprioception facilitated by mechanoreceptors, and help maintain dynamic balance ability [Hardy2008].

Interestingly, a previous study evaluated the ankle stiffness of pregnant women by optimizing the parameters of a two-segment lower limb model to fit experimental postural stability measurements [Ersal2014]. They found that the ankle stiffness of pregnant women who have experienced a fall was lower than the ankle stiffness of pregnant women who did not but similar to the ankle stiffness of nonpregnant women. This seems to indicate that greater ankle stiffness compensates the mass gain, the increase in ligament laxity, and the decreased neuromuscular coordination and allows to maintain balance. Incorporating an ankle support into the footwear could help increasing ankle support during pregnancy and this study provides some preliminary data to that effect.

1.2 Motivation and Objectives

Effect of pregnancy-induced mass gain

Although multiple studies focus on postural stability and indices, there is no consensus on the best measure of postural stability during pregnancy. This study isolates the main factor responsible for the increase in the risk of falling during pregnancy, namely the localized mass gain. One primary objective of this project is to determine the indices that quantify the effect of pregnancy-induced mass gain on postural stability during standing. The influence of pregnancy-induced mass gain on postural stability and the strategies developed by pregnant women to compensate for the mass gain remain elusive. One reason is the difficulty in recruiting subjects to perform large statistically significant cohort studies. Another reason is the difficulty in distinguishing from one another the effects of the complex pregnancy-induced physical changes on the measured postural stability. Using the relevant indices, we aim at understanding the influence of the pregnancy-induced mass gain only on postural stability.

Effect of footwear

No study comprehensively examined all possible indices to quantify the effect of footwear on postural stability.

By comparing three types of common footwear, flats, heels, and sports shoes, on healthy young subjects, this study aims at defining postural stability indices revealing the effect of footwear, if any. Using this knowledge, we wish to discuss the combined effect of footwear and pregnancy-induced mass gain.

As the potential positive influence of an ankle brace on postural stability has not been confirmed, there is little information on its effect during pregnancy, when joints are loosened by an increase in the hormone relaxin [Rasmussen2009]. One final goal for this study is to provide preliminary data on the potential benefits of stiffening the ankle joint during pregnancy to help compensate for the increase in mass and enhance postural stability. It is understood that the subjects of this study are not pregnant and hence, do not experience loosening of the joints the way a pregnant woman would. We aim at identifying possible changes in postural strategies linked to the presence of ankle support. In the future, this analysis can be utilized to mitigate the risk of falling in pregnant women by developing postural stability training and enhancing postural stability strategies.

CHAPTER II

EXPERIMENTAL AND STATISTICAL METHODS

2.1 Experimental Protocol

This study has been approved by the Oklahoma State University Institutional Review Board (IRB EN-18-9-STW).

2.1.1 Pregnancy simulation

The mass gain during pregnancy is localized to specific body segments. A model of the evolution of segmental masses during pregnancy has been developed by the lab [Haddox2020]. The volume and corresponding mass increase of each body segment at multiple stages of pregnancy have been computed from extensive anthropomorphic measurements of military pregnant women [Perkins1998] to create a full musculoskeletal model of the pregnant woman [Haddox2020].

To isolate the influence of pregnancy-induced mass gain on postural stability, the study was conducted on non-pregnant female subjects. The musculoskeletal model predicts the increase in mass of each segment of a non-pregnant subject during a hypothetical pregnancy, scaled by the subject's initial BMI. An increase in BMI of 0.62, 3.40, and 5.44 is predicted by the model for sessions 2, 3, and 4 corresponding to 12, 27, and 38 weeks of pregnancy. Using the subject’s height and weight, the increase in mass is computed from the increase in BMI. Finally, the proportion of the mass gain attributed to each segment is defined by the model. The computed weights are added to the upper trunk, lower trunk, buttocks, thighs, and lower legs using an Empathy belly, fitness strap-on weights, and a weighted harness.

Ten healthy non-pregnant women between 18 and 35 years old were recruited. As the army requires the BMI of military women to remain low and the mass gain highly depends on the initial BMI of the subject [Jensen1996], the model is limited to subjects with an initial BMI below 26. Apart from the BMI limitations, subjects with health conditions like diabetes, leg or back injuries or surgeries in the past, lower back pain, and any deformations of the spine were excluded. Finally, subjects were asked to confirm they could comfortably stand on their feet wearing weights.

Figure 1 Subject wearing the pregnancy weights.

2.1.2 Data collection

Five measurement sessions were conducted corresponding to five pregnancy stages: not pregnant, first trimester (12 weeks), second trimester (27 weeks), third trimester (38 weeks), not pregnant. The not pregnant session is repeated to account for learning effects and intersessions variability. The subjects were asked to participate in one measurement session every other day to avoid fatigue.

Subjects were given five minutes to adjust to the weights at the beginning of each session. The subjects stood on an instrumented treadmill barefoot for five minutes and their plantar pressure was recorded. The subject then stood on the treadmill for five periods of five minutes wearing five different footwear: flat shoes, low heels (lower than 3 cm) without ankle support, low heels with ankle support, sports shoes without ankle support, and sports shoes with ankle support in random order. Finally, the barefoot measurement was repeated to show any variabilities within the session and detect fatigue effects. The shoes were Bree pleated flats from American Eagle, Slip-Resistant Tressa Pump from safeTstep, and Gusto Sockfit Runner from Champion, all purchased from Payless ShoeSource. The ankle support is a neoprene hook and look ankle support brace from Bodyprox with an adjustable wrap to fit all subjects, purchased from Amazon. This is considered a flexible or semi-rigid brace.

The CoP position according to time was computed from the plantar pressure for each pregnancy stage and footwear. The CoP position was reported as two vector variables giving the coordinates of the CoP in the AP direction and in the ML direction, namely $CoP*^{AP}$ and $CoP*^{ML}$. Before any processing, the CoP coordinates are centered by subtracting the mean of the coordinates.

Figure 2 Footwear from Payless ShoeSource and corresponding degree of plantarflexion. Plantarflexion for the heels is significantly different from the sports and flats.

2.1.3 Postural stability Indices

A total of 22 postural stability indices categorized into time domain or frequency domain indices have been computed in MATLAB according to [Yamamoto2015].

Time domain indices

(1-2). Mean AP/ML

The indices Mean AP/ML (Eq. (1)) represent the mean position of the CoP in the AP and ML direction respectively.

$$Mean\ D = \frac{1}{N}\sum_{n=1}^{N} CoP_n^{*D} \qquad (1)$$

where D stands for AP or ML depending on the needed direction, n the time iteration, and N the number of recordings or number of time steps. Mean AP/ML characterizes the difference between the current posture and the vertical upright position.

In the following, the variables CoP^D, with D denoting AP or ML, are the standardized coordinates of the CoP in the direction D, as described in equation (2).

$$CoP^D = CoP_n^{*D} - Mean\ D \qquad (2)$$

(3). Log-LNG

Log-LNG represents the logarithm of the total length of the CoP path, computed from equation (3).

$$Log\ LNG = log\left(\sum_{n=1}^{N-1}\sqrt{(CoP_{n+1}^{ML} - CoP_{n}^{ML})^2 + (CoP_{n+1}^{AP} - CoP_{n}^{AP})^2}\right) \tag{3}$$

where n indicates the time iteration and N the total number of measurement points or time steps.

(4-5). Log-MV AP/ML

Log-MV AP/ML represent the logarithm of the mean CoP velocity in AP/ML direction (Eq. (4)).

$$Log\ MV\ DD = log\left(\frac{1}{T}\sum_{n=1}^{N-1}|CoP_{n+1}^{DD} - CoP_{n}^{DD}|\right) \tag{4}$$

where DD stands for AP or ML, n the time iteration, N the number of measurement points, and T the total measurement time.

(6). Angle

The Angle represents the absolute value of the angle in degrees between the major axis of the CoP 95% confidence ellipse and the ML-axis. The 95% confidence ellipse is the ellipse that encompasses 95% of the points of the CoP path. When the major direction of the CoP motion is parallel to the ML direction, Angle = 0°, and when the major direction of the CoP motion is parallel to AP direction, Angle = 90°.

(7). Flattening

The Flattening represents the ratio of flattening of the CoP 95% confidence ellipse (Eq. (5)).

$$Flattening = 1 - \frac{short_{el}}{long_{el}} \tag{5}$$

where $short_{el}$ and $long_{el}$ denote the length of the major and minor axes of the ellipse. When the Flattening equals zero, the ellipse is a circle. The ellipse becomes flat as the Flattening reaches one.

(8-9). MP3 and Log-Slope-MP

The Sway Density Curve (SDC) describes how densely a sway trajectory lies locally as a function of time. More precisely, the SDC indicates changes in time duration of how long CoP trajectory stays locally and time-continuously inside a circle with a radius of R mm, centered at a CoP point at every sampling instant of time. The SDC exhibits an oscillatory waveform indicating that CoP stays locally for a period of time (corresponding to a peak of the SDC) and then moves to another location (corresponding to a valley of the SDC). The SDC was low-pass filtered using a fourth-ordered zero-phase lag Butterworth filter with a cut-off frequency 12.5Hz. The index MP3 quantifies the mean of the peak values of the oscillatory SDC for R=3 mm. Log-Slope-MP represents the log of the slope of the curve of MP values versus R from 2 mm to 5 mm, that is the curve of MP2 to MP5.

(10-11). Zero-Cross-V-AP/ML

The indices Zero-Cross-V-AP/ML are the number of zero-cross events, defined as the instants of time when low-pass filtered $\mathrm{CoP}^{\mathrm{AP/ML}}$ velocity crosses the zero axis, for the entire time span. The cut-off frequency of the CoP velocity filter was set as 2.5 Hz.

(12-15). Log-Alpha AP/ML and Beta AP/ML

The indices Log-Alpha AP/ML are the logarithm of the parameter α of

The distribution of time intervals between two zero-cross events in the $\mathrm{CoP}^{\mathrm{AP/ML}}$ velocity profile is plotted as a histogram and fitted with a probability density function of the Gamma distribution, *p(x)*, defined in equation (6), with *x* being the time interval.

$$p(x) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1}.e^{-\frac{x}{\beta}} \qquad (6)$$

Contrary to the previous index, the velocity here was not filtered to determine *x*. Log-Alpha AP/ML and Beta AP/ML are the logarithm of the α parameter and the β parameter in the Gamma distribution.

Frequency domain indices

Frequency domain indices are based on the CoP power spectral density (PSD) functions, computed by Fast Fourier Transform of the CoP path, or the CoP position in the AP/ML directions.

<u>(16). Log-Power</u>

The Log-Power represents the log of the CoP total power, which is the area under the CoP path PSD from 0.15 to 5 Hz (Eq. (7)).

$$Log\ Power = log \sum_{m=i}^{j} m\Delta f G[m] \qquad (7)$$

where G[m] is the discrete power spectrum density function of the CoP path, $\triangle f$ the incremented frequency, and *i* and *j* the discretized frequency values corresponding to 0.15 Hz and 5 Hz.

<u>(17-18). PF50 and PF95</u>

The indices PF50 and PF95 represent the frequencies where 50% and 95% of the total power of the CoP path is found, respectively. To compute this, the smallest discretized frequency value u^{X} that satisfies equation (8) is computed.

$$\sum_{m=i}^{u^X} m\Delta f G[m] \geq X\ Power \qquad (8)$$

where X = 50% for PF50 and 95% for PF95. Then $PFX = u^X \Delta f$.

<u>(19-22). Slopes of the PSD</u>

These indices characterize the scaling exponents of the power-law shaped PSD of $CoP^{AP/ML}$. The slope of the log-log plot of the PSD in the low and high frequency regions is determined through curve fitting. Slopes-L AP/ML is the slope of the log-log PSD of $CoP^{AP/ML}$ at low frequency (0.04-0.5 Hz). Slope-H AP/ML is the slope of the log-log PSD of $CoP^{AP/ML}$ at high frequency (0.5-1 Hz).

Table 1 Summary of Postural stability indices [Yamamoto2015]

Number	Index Name	Description
Time domain		
1	Mean AP	Mean position of sway in AP direction
2	Mean ML	Mean position of sway in ML direction
3	Log-LNG	Log of total path length of CoP trajectory
4	Log-MV AP	Log of mean CoP velocity in AP direction
5	Log-MV ML	Log of mean CoP velocity in ML direction
6	Angle	Absolute value of angle between major and ML axis of 95% confidence ellipse
7	Flattening	Flattening of 95% confidence ellipse
8	MP3	Mean Peak value on sway density curve at R=3
9	Log-Slope-MP	Log of slope of regression line of graph for MP versus R belongs [2,5]
10	Zero Cross-V AP	The number of zero crosses of low-pass filtered CoP velocity in AP direction
11	Zero Cross-V ML	The number of zero crosses of low-pass filtered CoP velocity in ML direction

12	Log-Alpha AP	Log of shape parameter of Gamma distribution fitted to the duration of mean CoP velocity crosses in AP direction
13	Log-Alpha ML	Log of shape parameter of Gamma distribution fitted to the duration of mean CoP velocity crosses in AP direction
14	Beta AP	Scale parameter of Gamma distribution fitted to the duration of mean CoP velocity crosses in AP direction
15	Beta ML	Scale parameter of Gamma distribution fitted to the duration of mean CoP velocity crosses in ML direction
Frequency domain		
16	Log-Power	Log of total power of CoP path
17	PF 50	50% power frequency of CoP
18	PF 95	95% power frequency of CoP
19	Slope-L AP	Slope at low frequency of PSD of CoP in AP direction
20	Slope-L ML	Slope at low frequency of PSD of CoP in ML direction
21	Slope-H AP	Slope at high frequency of PSD of CoP in AP direction
22	Slope-H ML	Slope at high frequency of PSD of CoP in ML direction

2.2 Statistical Analysis

Two-way repeated-measures ANOVA

To determine the effect of pregnancy-induced mass gain and footwear condition on postural stability, we performed a two-way repeated-measures Analysis of Variance (ANOVA) on each of the 22 indices, using the statistics software SPSS (IBM, version 22). An ANOVA is a method that provides a statistical test of whether two or more population means are equal. A two-way ANOVA is used to estimate this difference of means when two independent variables affect the changes in one dependent variable. A repeated-measures ANOVA compares means across the dependent variable that are based on repeated observations on the same subject. A two-way repeated-measures ANOVA was thus used to analyze the effect of pregnancy-induced mass gain and footwear conditions (two independent variables) on a postural stability index (one dependent variable), which is measured repeatedly on one subject for every pregnancy stage (repeated measures).

Effect of pregnancy-induced mass gain and footwear

The two-way repeated-measures ANOVA was performed for each index with the values of the postural stability index as input according to weeks of simulated pregnancy (0, 12, 27, 38 weeks corresponding to non-pregnant, first, second, and third trimester) and to footwear (barefoot, flats, heels, sport shoes). The repeated non-pregnant condition was performed to check inter-session variability and is excluded from this analysis. The repeated barefoot condition is also excluded as this measurement was performed to assess intra-session variability, namely fatigue effects. The conditions including ankle braces, sports with brace and heels with brace, will be studied separately.

Since this study is conducted on human subjects and the number of subjects is relatively low, a significance level of 10% would not be statistically strong enough. We set the level of statistical significance at 5% and perform the analysis of postural stability only from the indices that are significantly at the 5% level. As the level of significance was assumed to be 5%, the effect of a factor on an index is considered significant when the probability of the observed correlation being random is lower than 0.05.

The ANOVA can provide many statistical outputs but the most useful for this study are the within-subject effects. The computed value is the significance level of the effect of the factors, pregnancy-induced mass gain and footwear, or of their interaction on that particular postural stability index. Significant effects for all factors or interactions are tabulated with their probability significance values for further discussion.

Effect of ankle braces

To understand the effect of ankle braces, two-way repeated-measures ANOVAs are performed on all indices at four pregnancy stages (non-pregnant, first, second, and third trimester) with two footwear conditions: with and without braces. Thus, this ANOVA is separately performed for heels and sports shoes. The level of significance was 5%.

Presentation of indices and normalization

Indices are presented in real values, except for the Mean AP/ML indices which are computed in absolute values as the deviation from perfect vertical can be in any direction. Index values are normalized with respect to the non-pregnant stage to show the influence of pregnancy-induced mass gain, with respect to the barefoot condition to show the influence of footwear, and with respect to the without brace condition to show the influence of braces. All normalizations take place for each subject before averaging and computing the standard deviation for all subjects.

CHAPTER III

RESULTS – EFFECTS ON POSTURAL STABILITY

The statistical analysis of all the indices for the effect of pregnancy-induced mass gain and footwear conditions is summarized on figure 3, including the level of significance of the effect of each factor. Stage indicates the effect of pregnancy-induced mass gain denoted as pregnancy "stages" and condition indicates the effect of footwear. Temporal represents the axis of time-domain indices, temporalvel the axis of indices depending on the CoP velocity, and spectral the axis of frequency domain indices. Indices not represented on the summary exhibited levels of significance above 10%.

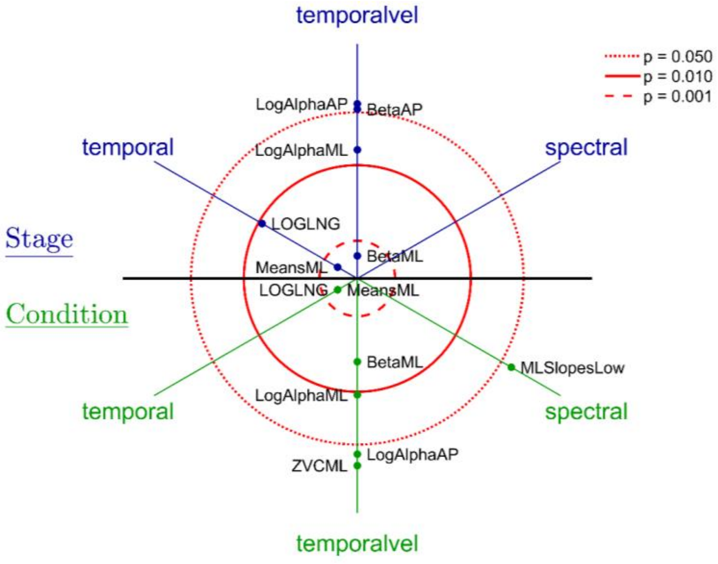

Figure 3 Statistical results of the pregnancy-induced mass gain and footwear effects on the indices.

Multiple postural stability indices on the temporal and temporalvel axes significantly vary with pregnancy-induced mass gain and footwear. The two factors studied do not have any significant effect on the spectral indices. Further trend analysis will highlight the effects of mass gain and footwear on postural stability. All trend analyses are performed using the average value of the index for all the subjects.

3.1 Effect of pregnancy-induced mass gain

Four out of 22 indices show a significant effect of pregnancy-induced mass gain with a significance level below 5%: Mean-ML, Log-LNG, Log-Alpha-ML, and Beta-ML. These 4 indices are time-domain indices with Log-Alpha-ML and Beta-ML being velocity-based parameters. Interestingly, there is no effect of pregnancy-induced mass gain on indices characterizing postural stability in the AP direction.

Table 2 Statistical significance values for the effect of pregnancy-induced mass gain

Index Name	Probability
Mean ML	p = 0.000
Log-LNG	p = 0.009
Log-Alpha ML	p = 0.016
Beta ML	p = 0.000

The evolution of these indices with pregnancy-induced mass gain is plotted in absolute value and normalized with respect to the non-pregnant measurements (Figs 4-7). Standard deviations indicate the inter-subject variability. Considering the high standard deviation amongst measurements, these plots are included to detect trends only.

The absolute value of Mean ML increases as pregnancy-induced mass increases (Fig. 4). This indicates that the posture bias increases in the ML direction when the mass increases so subjects tend to lean on one side. Interestingly, a similar posture bias is not observed in the AP direction. The normalized Mean ML shows that the bias increases for the barefoot condition more than for other footwear. For flats and heels, the relative increase is small compared to sports and barefoot.

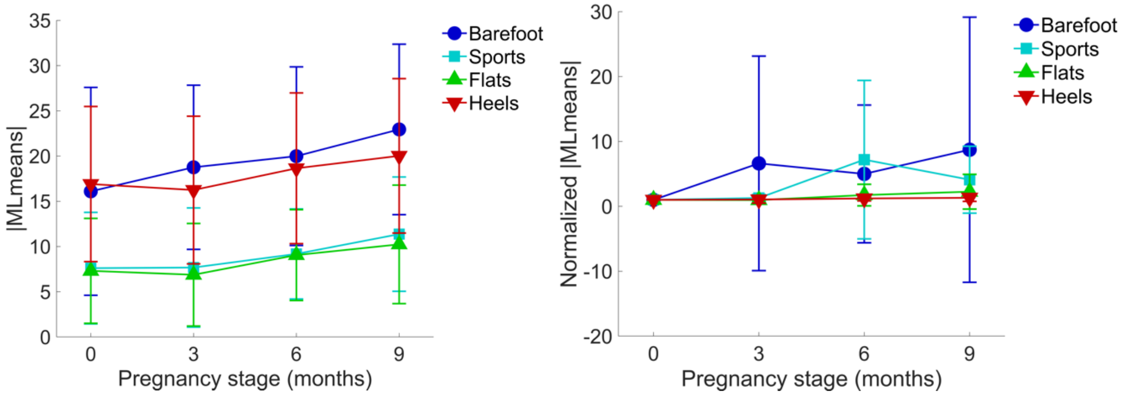

Figure 4 Effect of pregnancy-induced mass gain on Mean ML and normalized Mean ML

Log-LNG and normalized Log-LNG decrease as pregnancy-induced mass increases (Fig. 5). This indicates a smaller total displacement of the CoP when the mass increases, either due to slower movements or smaller oscillations. Either way, a decrease in Log-LNG indicates a decrease in the mean CoP velocity.

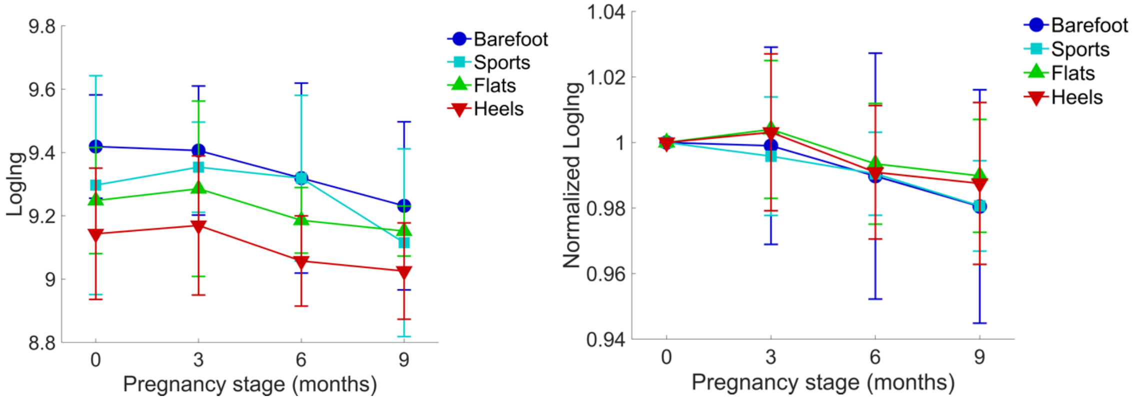

Figure 5 Effect of pregnancy-induced mass gain on Log-LNG and normalized Log-LNG

Log-Alpha ML and normalized Log-Alpha ML decrease as pregnancy-induced mass increases (Fig. 6). Normalization of Log-Alpha ML indicates that Log-Alpha is almost constant for Flats and barely decreasing for Sports. Beta ML and normalized Beta ML increase steeply as pregnancy-induced mass increases in the second and third trimesters (Fig. 7). Both these observations indicate a decrease of the very fast oscillatory components in the CoP velocity profile.

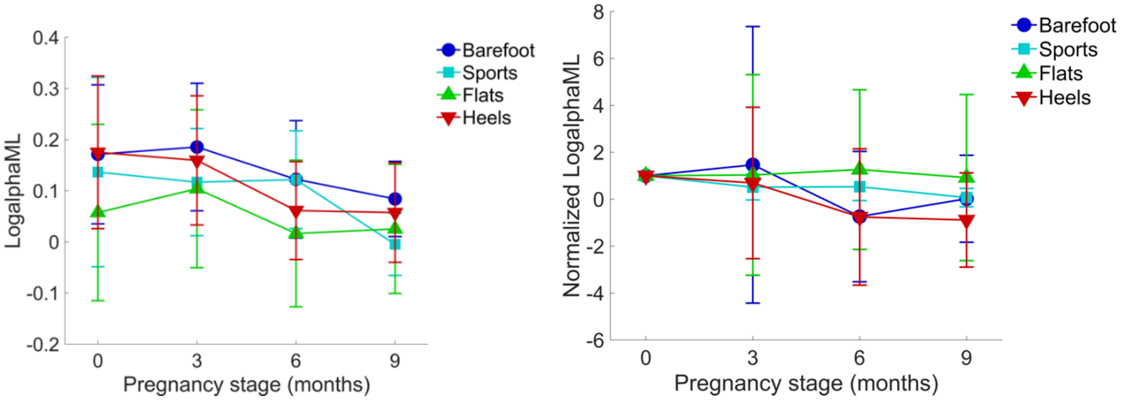

Figure 6 Effect of pregnancy-induced mass gain on Log-Alpha ML and normalized Log-Alpha ML

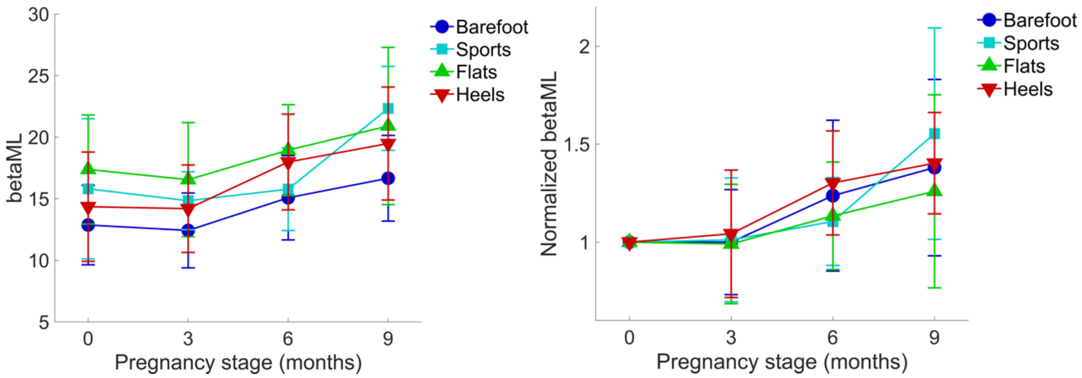

Figure 7 Effect of pregnancy-induced mass gain on Beta ML and normalized Beta ML.

3.2 Effect of footwear during simulated pregnancy

Four out of the 22 indices show an effect of footwear with significance below 0.05. All four indices are identical to the indices exhibiting an effect of pregnancy-induced mass gain. They are time domain indices characterizing the ML direction.

Table 3 Statistical significance for the effect of footwear

Index Name	Probability
Mean ML	p=0.000
Log-LNG	p=0.000
Log-Alpha ML	p=0.011
Beta ML	p=0.004

The value of absolute Mean ML is normalized with the barefoot value at each pregnancy stage (Fig. 8). The normalized Mean ML goes from being higher than the barefoot value at the non-pregnant stage to being lower or similar to the barefoot value at subsequent pregnancy stages. Sports and flats show a significant decrease of Mean ML compared to barefoot when pregnancy mass is added. This would tend to indicate less bias of the posture on the right or left when the subjects are wearing shoes.

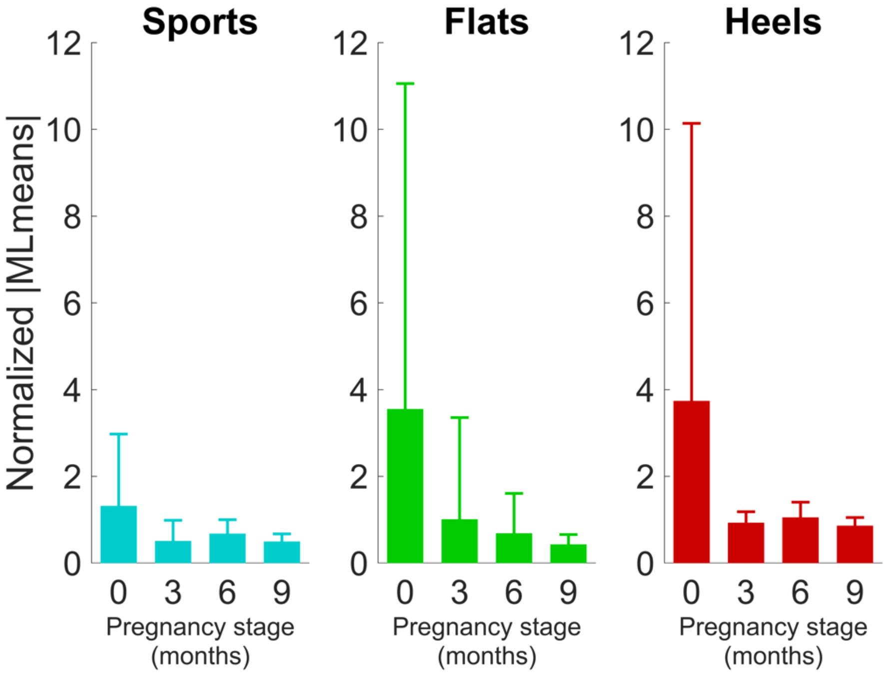

Figure 8 Effect of footwear on normalized Mean-ML at each pregnancy stage

The Log-LNG values normalized with respect to the barefoot condition show a small decrease for sports, flats, and heels for all pregnancy stages (Fig. 9). So the CoP path is slightly shorter when the subjects are wearing shoes.

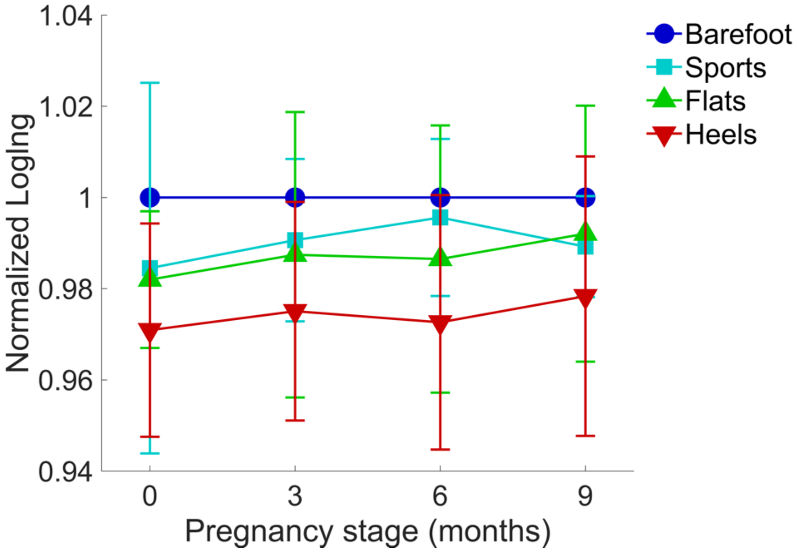

Figure 9 Effect of footwear on normalized Log-LNG at each pregnancy stage

The values of Log-Alpha ML normalized with respect to the barefoot result are plotted for each pregnancy stage (Fig. 10). The Log-Alpha values for all footwear conditions are fairly close to the barefoot value for all pregnancy stages except for the flats Log-Alpha ML at the second and third trimesters, which is higher. Beta ML values are higher for any footwear condition than the ones obtained barefoot (Fig. 11), with the flats Beta ML being the highest in the first and second trimesters and the sports Beta ML the highest in the third trimester. Increase in Beta ML values indicate a decrease in the very fast oscillatory components of the CoP velocity in the ML direction.

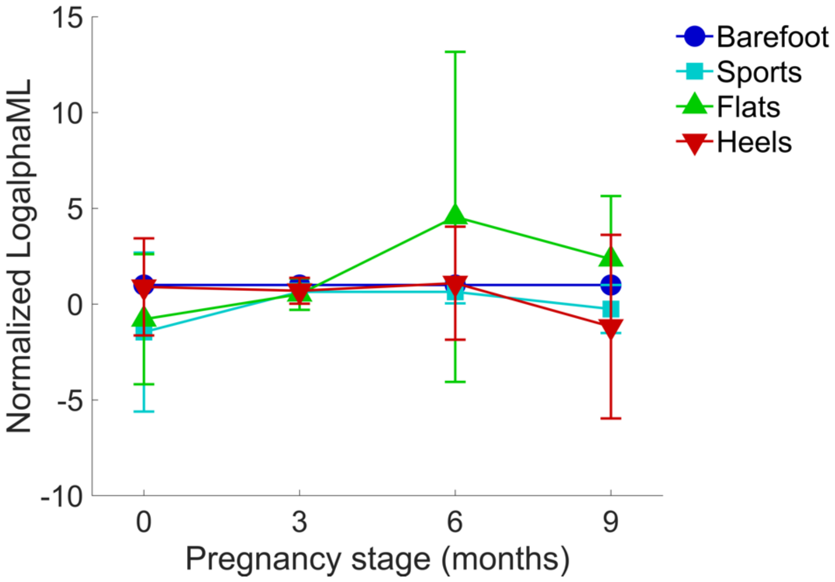

Figure 10 Effect of footwear on normalized Log-Alpha-ML at each pregnancy stage

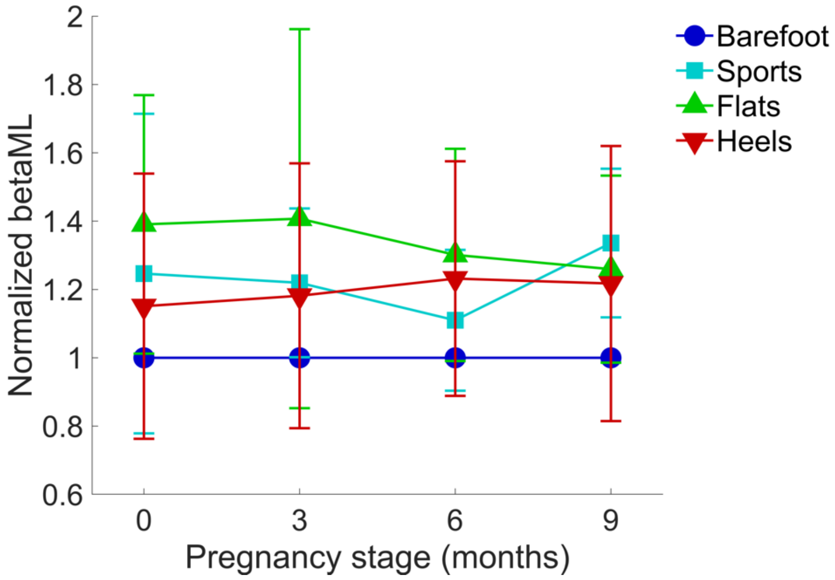

Figure 11 Effect of footwear on normalized Beta-ML at each pregnancy stage

3.3 Effect of the interaction between mass gain and footwear

The effect of the interaction between pregnancy-induced mass gains and footwear on postural stability is included in the ANOVA. There are no index sensitive to the effect of the interaction with a statistical significance below 5%. Since some indices are significantly sensitive to both effects, it seems to indicate that the factors do not interact, that is the influence of footwear is identical no matter what mass is added to the subject and the influence of pregnancy-induced mass gain does not depend on the footwear.

3.4 Effect of ankle brace

Five indices are sensitive to the effect of ankle braces with Sports. They characterize the postural stability in AP and ML direction and pertain to both the time domain and frequency domain.

Table 4 Statistical significance for the effect of ankle braces with Sports

Index Name	Probability
Time-domain	
Beta AP	p = 0.046
Beta ML	p = 0.033
Log-MV AP	p = 0.013
Frequency-domain	
Log-Power	p = 0.036
PF 95	p = 0.023

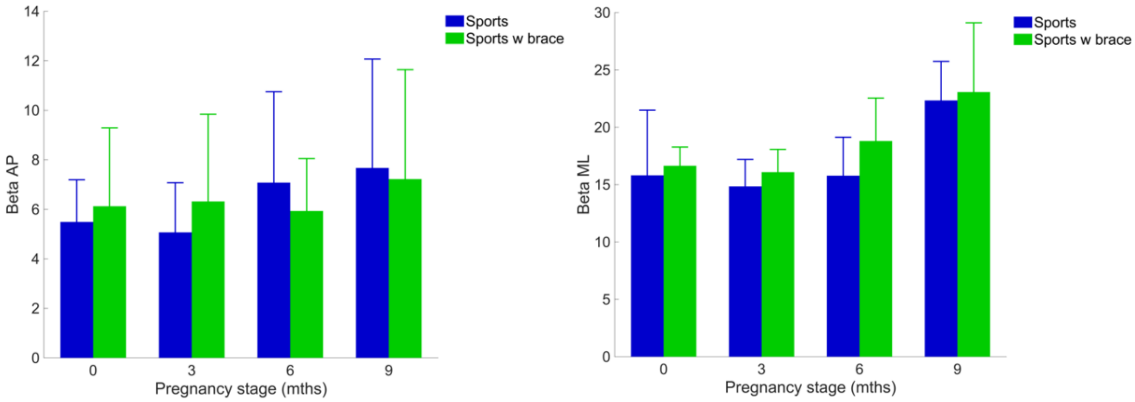

Figure 12 Effect of ankle brace on Beta AP and Beta ML

Beta AP and Beta ML values for Sports with and without ankle braces are presented at each pregnancy stage (Fig. 12). Beta AP increases with the mass gain without ankle braces. This increase seems to be mitigated for Sports with ankle braces. So, the large decrease of the very fast oscillatory components of the CoP velocity in the AP direction due to mass gain is not seen when subjects wear ankle braces. However, without added mass, Beta AP is higher when ankle braces are worn, indicating a decrease of the fast-oscillatory components as an effect of the ankle brace to begin with.

Similarly, Beta ML increases with added pregnancy mass. The addition of ankle braces slightly raises the value of Beta ML at all pregnancy stages compared to the value without ankle braces. So, adding ankle braces actually intensifies the decrease of the very fast oscillatory component of the CoP velocity in the ML direction.

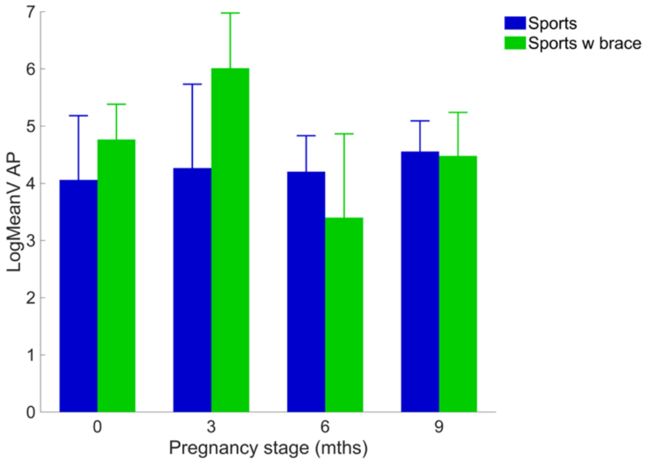

Figure 13 Effect of ankle brace on Log-MV AP

Log-MV AP is higher when not pregnant and in the first trimester and then lower, although not significantly, in the second and third trimester for Sports with brace compared to without (Fig. 13). An increase of Log-MV AP indicates an increase of sway [Kouzaki2012] when wearing ankle braces.

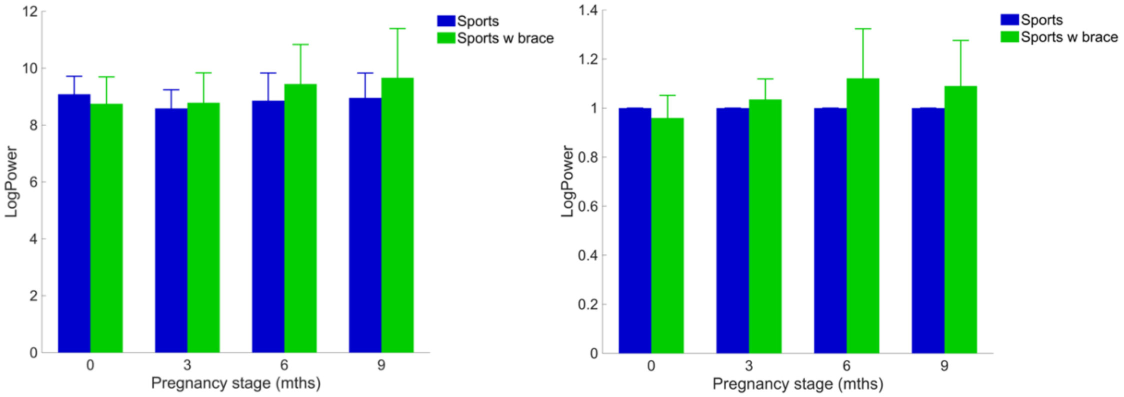

Figure 14 Effect of ankle brace on Log-Power

The addition of ankle braces slightly decreases Log-Power when not pregnant, but increases it when subjects are loaded with simulated pregnancy masses (Fig. 14). The effect of ankle braces increases with the added mass. As a measure of sway, an increase in Log-Power has been thought of indicating a decrease in postural stability [Prieto1996].

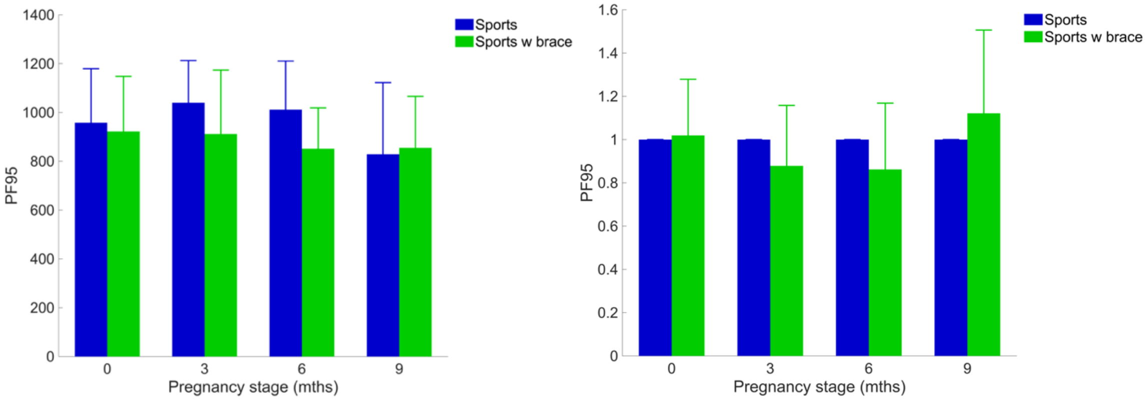

Figure 15 Effect of ankle brace on PF95

PF95 is lower for Sports with ankle braces compared to Sports without, except for the third trimester where it is slightly higher (Fig. 15). Interestingly, at the first and second trimesters, the effect of the ankle braces seems to be accentuated by the added mass, meaning the decrease is more important than at the not pregnant stage. A decrease in PF95 seems to indicate a global increase in postural stability.

There is just one index that is sensitive to the effect of ankle braces with heels: Mean ML. This seems to indicate a limited effect of ankle braces when the subject is wearing heels.

Table 5 Statistical significance for the effect of braces with Heels

Index Name	Probability
Mean ML	p = 0.003

The value of Mean ML is lower in Heels with braces compared to without (Fig. 16), indicating that subjects are closer to a perfect vertical upright position.

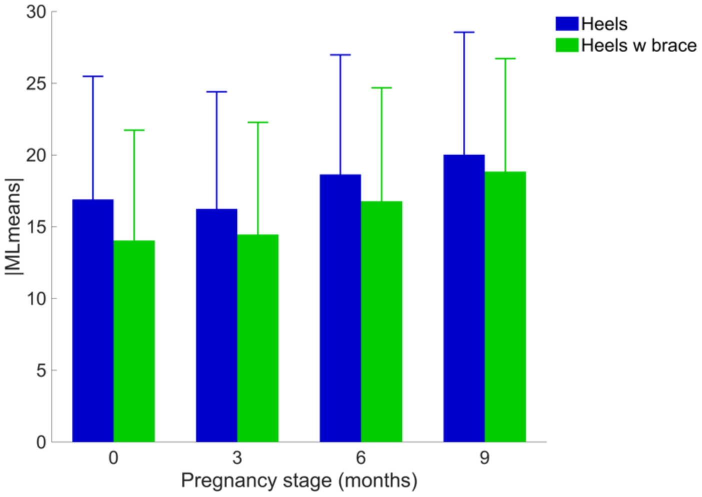

Figure 16 Effect of ankle brace on Mean ML

CHAPTER IV

DISCUSSION

Our statistical analysis indicates that only 4 of the 22 indices exhibited significant differences between pregnancy stages and footwear conditions, namely Mean ML, Log-LNG, Log-Alpha ML, and Beta ML. First, this confirms that, as hypothesized, pregnancy mass and footwear significantly affect postural stability, as characterized by these indices. And these 4 indices are optimal parameters to define the effect of either pregnancy-induced mass gains or footwear conditions.

Interestingly, the same set of 4 indices shows significance of both factors. The significance of the same set of indices demonstrates that the effect of the two factors on postural stability can be detected by the same characteristics of the CoP. They are all in the time-domain and either in all directions combined or specifically in the ML direction. In other words, no spectral index and no index characterizing the CoP in the AP direction exhibited an effect of pregnancy-induced mass gain or footwear.

Moreover, all the indices showing significant effect of mass gain and footwear are deemed individual-specific by Yamamoto et al. [Yamamoto2015]. Universal indices tend to behave similarly for all subjects while individual-specific indices directly correlate with body parameters, as proven by correlation with body inertia.

Logically, uneven mass gain modifies the body inertia and hence the individual-specific indices. The impact of footwear remains unclear and will be discussed in details below. The pregnancy-induced mass gain and footwear condition have two main effects:

- *ML body lean*: Mean ML characterizes a body lean on a favored side, *i.e.* a departure from a perfect vertical symmetrical position.
- *Increase or decrease in CoP sway and velocity*: Log-LNG characterizes the amount of CoP movements in a given test time. Thus Log-LNG directly correlates with the mean CoP velocity. Log-MV AP directly measures the mean CoP velocity. Log-Power is the power of the CoP velocity indicating an increase or decrease of the CoP velocity.
- *Shift of CoP velocity frequency*: Log-Alpha ML and Beta ML or AP detect changes in the very fast oscillatory components of the CoP velocity [Yamamoto2015]. Since, the slow components of the velocity are invariant, these indices also indicate a change in mean CoP velocity. PF95 is a measure of the frequency range of the CoP velocity PSD function.

Characterizing postural stability based solely on CoP locations has been previously criticized [Doyle2004], and parameters based on CoP velocity are a more accurate assessment of postural control since they are linked to postural feedback [Masani2003].

4.1 Effect of pregnancy-induced mass gains on postural stability

4.1.1 AP versus ML influence

The indices sensitive to the effect of pregnancy-induced mass gain describe postural stability in the ML direction only. This indicates that the mass gain has a significant effect on the postural stability in the ML direction but no significant effect in the AP direction.

This contradicts multiple measurements on pregnant subjects. Previous studies found that the lateral postural stability of pregnant women is preserved during pregnancy [Jang2008, Nagai2009, OpalaBerdzik2015], which has been thought to result from the adaptation of stance width [Jang2008], or the even distribution of mass gain in the frontal plane [OpalaBerdzik2015]. Only one study found a decrease of postural stability in the ML direction [Inanir2014]. Danna-Dos-Santos et al. [Danna-Dos-Santos2018] found a decrease in sample entropy of the CoP in the ML direction indicating more regular ML patterns of oscillation. The same studies showed that postural stability in the AP direction decreases with pregnancy [Nagai2009, Oliveira2009, Inanir2014, Danna-Dos-Santos2018] or remains unchanged [OpalaBerdzik2015].

One of the main differences between the present study and the literature is that our protocol isolates one pregnancy-induced physical change, namely unevenly distributed mass gain. Ergo, it excludes a large list of anatomical, physiological, and hormonal changes impacting postural stability, such as memory problems and difficulty concentrating, anterior shift in the location of the center of mass, increased ligamentous laxity, decreased neuromuscular and coordination, swelling in arms and legs, decreased abdominal muscle strength, or increased spinal lordosis [McCrory2010]. The interpretation of this observation is twofold. First, it indicates that the change in AP postural stability may be due to a combination of long-term effects of the mass gain, such as the increase in spinal lordosis and the shift in CoM, with other physiological and hormonal effects. Second, pregnant women may change their posture to compensate for the lack of postural stability in the ML direction due to the added mass by adapting their stance width and their control strategies. Again, this adaptation would happen over a time scale larger than the one-hour sessions of this study.

4.1.2 ML body lean

The effect of pregnancy-induced mass is observed in the index Mean ML, which measures the lean of the body on either side. As the CoP shifts away from the middle line between the feet, the asymmetry of the posture is accentuated and the CoP moves closer to the boundary of the base of support. Consequently, an increase in Mean ML reflects a decrease in postural stability, *i.e.* an increase in the risk of falling.

To maintain balance, the CoP and the vertical projection of the CoM should coincide. As the distance CoP-CoM increases, the risk of falling increases [Ersal2014]. To maintain stability, the body keep the CoP and CoM projection as close as possible by adapting posture and segment position. For example, if the CoM moves anteriorly and approaches the boundary of the base of support, the foot automatically moves forward to reposition the CoM projection at the center of the base of support, close to the CoP. So, the displacement of the mean position of the CoP reflects the displacement of the CoM of the body.

Movements of the CoM during pregnancy have been measured since 1943 [Fries1943, OpalaBerdzik2010]. More recently, the shift of the body CoM, forward and sideway, has been precisely measured comparing regression, volume measurement and weighted sum [Catena2018, Catena2019]. Our study only found a significant shift of the CoP in the ML direction. The shift of the CoM is thought to correspond to an adaptation of the body to the added weight. This body adaptation is not immediate and, since we are placing weights on subjects for less than an hour, any potential adaptation is too small to impact the CoP.

4.1.3 Decrease in CoP velocity

The decrease in Log-LNG and Log-Alpha ML combined with the increase in Beta ML indicates a decrease in the very fast oscillatory components of the CoP velocity and hence, a decrease in mean velocity.

LNG has been thought to negatively correlates with postural stability [Chastan2008, Stylianou2011]. In other words, when the postural stability decreases, the CoP displacements increase, which obviously results from an increase in mean CoP velocity. Following this reasoning, numerous studies have shown a decrease in postural stability during pregnancy. They quantified the postural stability with indices that relate to the CoP velocity, such as the sway (LNG in our study) [Butler2006, Jang2008, Nagai2009, Oliveira2009, Dana-Dos-Santos2018], the AP sway [Jang2008], the CoP velocity [Jang2008], the power [Oliveira2009], the ML power [Nagai2009]. Notably, Opala-Berdzik et al. [OpalaBerdzik2015] failed to see any significant change in postural stability with pregnancy using similar indices.

In this study, the Log-LNG decreases with mass gain signaling a decrease in mean velocity, which is corroborated by Log-Alpha ML and Beta ML showing a decrease in the very fast components of the CoP velocity in the ML direction. McCrory et al. [McCrory2010] made a similar observation showing a decrease in sway as a response to perturbations evaluating dynamic postural stability. They suggested two possible origins for this behavior. First, the sway response may measure specific sensory processing capabilities rather than biomechanical changes. Several studies have mentioned a large influence of visual input on the postural stability in the third trimester [Butler2006, Oliveira2009] and subjects mentioned impaired vision as a contributing factor of their fall [Dunning2003]. Since the subjects in our study are not actually pregnant and kept their eyes open, they do not experience any of the vision impairment or potential neurological deficit in processing visual inputs. So this cause would not apply here.

The second potential cause of sway reduction with a decrease of postural stability is the rigidity strategy, due to a reduction in rotation amplitude [Foti2000, Wu2004] and a transition from out-of-phase to in-phase rotation [McCrory2014] of the thorax and pelvis. Studies on healthy young subjects also mention a rigid strategy to increase postural stability by anticipatory co-contraction of leg and trunk muscles [Mohapatra2014]. As the very fast components of the CoP velocity represent the anti-phase coordinated trunk-leg movement [Yamamoto2015], the decrease in Log-Alpha ML and increase in Beta ML indicate a decrease of the anti-phase trunk-leg movements and confirm the rigidity strategy. Namely, subjects are sacrificing efficacy for safety as a response to a perceived instability and fear of falling [Adkin2002]. The muscle contraction and reduction of torso rotation leads to a reduced CoP sway but also decrease the ability of the body to quickly respond to external perturbations, thus increasing the risk of falling [Adkin2002].

Results indicate that the rigidity strategy is hence the short-term response of the body to the increase in mass. The anticipatory muscle co-contraction would lead to early muscle fatigue if subjects had to maintain the pregnancy-induced mass gain for long periods. Since the measurement sessions last less than an hour, subjects did not have to develop long-term adaptation strategies. This remains a limit of the protocol, which allows to isolate the influence of the mass gain but on a time scale much shorter than an actual pregnancy.

4.2 Influence of footwear conditions on postural stability

4.2.1 AP versus ML influence

Footwear has a significant effect on the postural stability in the ML direction but not in the AP direction. Several studies quantified the effects on postural stability of heels [Mika2016, Emmanouil2018], occupational footwear [Chander2014], sandals [Alghadir2018], sports [Brenton-Rule2011], and so-called unstable shoes [Landry2010, Federolf2012]. However, results and interpretations regarding postural stability are inconsistent [Federolf2012]. Studies showed no influence of sandals on postural stability [Alghadir2018], an increase in global sway (LNG) with 40 mm-high heels [Mika2016], an increase in AP sway with sport shoes [Brenton-Rule2011], and an increase in AP and ML sway with high heels [Emmanouil2018]. Comparing literature results is particularly difficult for footwear as there is no standardization of the footwear used to detect postural stability changes.

We found an increase in ML sway with 45 mm-high heels that correlates with the reported increase in global sway with 40 mm-high heels [Mika2016]. However, sway in both AP and ML directions increased with 65 mm- and 110 mm-high heels [Emmanouil2018]. The lower heel height may not change the plantarflexion angle enough to disrupt muscle function, which would explain the lack of effect in the AP direction.

AP sway also increases with sport shoes compared to barefoot [Brenton-Rule2011]. However, the study was performed on older adults (mean age 74 years old). Older subjects often exhibit a loss of proprioception, which, combined with soft insoles, tends to decrease sensory information, and thus impair postural balance. Increasing the AP sway could be a mechanism to enhance sensory feedback at the ankle joint. Young healthy subjects did not exhibit age-related sensory decline and therefore did not need to increase AP sway.

4.2.2 ML body lean

An increase of the lean indicates a decrease of the distance between the CoP and the boundary of the base of support. Consequently, postural stability decreases when the lean increases. Sport and flats have a significant effect on Mean ML. Footwear, other than heels, decreases body lean compared to barefoot throughout pregnancy, which confirms that wearing shoes increases ML postural stability.

Footwear can improve foot and ankle proprioception, by affecting cutaneous proprioception through collar height and stiffness [Lord1991, Chander2014, Mika2016, Aboutorabi2018, Emmanouil2018, Li2019]. For example, the increase in ankle proprioception and stiffness from low top shoes to high collar shoes lowers the ML sway [Chander2014]. In our study, sports provided a tight fit that likely increased foot proprioception, whereas flats provided harder collar support that may enhance ankle proprioception.

The lack of effect when wearing heels seems to contradict the literature. When wearing heels, the sway decreases through an increased use of the plantarflexor muscles around the ankle, and additional control may be provided using the hip muscles. Winter and Eng (1995) showed that different joints control sway in different directions: the ankle joints regulate the AP sway, whereas the hip joints regulate the ML sway. In addition, there only exists a handful of muscle synergies ensuring postural balance [TorresOviedo2007]. The plantarexed neutral position adopted when wearing heels may alter ankle muscle activations, forcing the body to rely on hip muscles. The increased ML postural stability may then directly result from the necessary use of the hip muscles to ensure AP postural stability. One reason explaining the lack of effect in our study is the low heel height combined with a large base of support (40 mm x 35 mm) when compared to traditional high heels (10 mm x 10 mm) [Emmanouil2018]. Discrepancy between these studies indicate that the base area under the heel may play a critical role regarding postural stability.

4.2.3 Decrease in CoP velocity

The decrease in Log-LNG combined with the increase in Beta ML indicates a decrease in the very fast oscillatory components of the CoP velocity and hence, a decrease in mean velocity and sway. Consequently, postural sway decreases from barefoot to sports and flats, and from flats to heels, at all pregnancy stages.

A decrease in sway could characterize a more stable system [Paillard2015, Mika2016, Emmanouil2018] and an increase in sway has been measured when wearing heels [Mika2016]. Considering this interpretation, our results could indicate that footwear enhance postural stability, mainly through an increase in foot and ankle proprioception. However, we do not expect heels to facilitate postural stability compared to sports. A more relevant interpretation is that subjects, as response to the fear of falling, use the rigidity strategy to ensure postural stability [Adkin2002], as discussed in section 4.1. The increase in rigidity and decrease in CoP velocity also indicates a higher risk of falling because the system is less likely to react efficiently to external perturbations. This behavior is mostly due to increased muscular contractions necessary to tighten the motion. Although these findings seem reasonable concerning heels, they may seem counter-intuitive when considering sport shoes and flats. As mentioned, footwear may enhance foot proprioception around the heel and ankle, but they may dull plantar proprioception if the insole is too soft [Robbins1995].

Unfortunately, we did not ask our subjects if they were used to wearing heels but, if it was not the case, an increased fear of falling may explain these results. Subjects were instructed to keep their eyes opened, which may have skewed the results since visual feedback is believed to play a more important role in postural control than proprioception, although less for younger subjects than older ones [Doyle2004].

4.3 Influence of ankle brace on postural stability

Numerous indices detect the influence of ankle braces when wearing sports, namely Beta AP, Beta ML, Log-MV AP, Log-Power, and PF95, while only Mean ML changes with ankle braces when wearing heels. Wearing an ankle brace has a more predominant effect on postural stability with sports than with heels. Heels already drastically reduce the postural stability and subjects tend to rigidify their posture to compensate. Consequently, the additional rigidity provided by the ankle brace has little influence on the postural stability measures.

4.3.1 Reduction in ML body lean

Comparison of Mean ML wearing heels with and without braces indicates a decrease of body lean in the ML direction with the ankle braces. Subjects tend to maintain a more upright body position with ankle braces. As the ankle braces are assumed to act mainly in the ML direction, this effect is expected. It is however unexpected that ankle braces would not have a similar effect with sport shoes. We assume that the subjects were leaning less with sports shoes and hence the effect of ankle braces on this index was not significant.

4.3.2 Increase in CoP velocity

When wearing Sports, Log-MV AP increases with braces at the not pregnant and first trimester stages. It seems to slightly decrease at the second and third trimester stages. In addition, Log-Power increases with braces. Both indices characterize an increase in the CoP velocity. The added pregnancy mass leads to a decrease in postural stability. As a response, subjects develop a rigidity strategy, discussed in section 4.1. The muscle co-contractions lead to a decrease in measured sway, detected by a decrease in CoP velocity. The increase in CoP velocity with braces indicates less muscle contractions and rigidity, meaning the braces are helping counteract the effect of added pregnancy mass on the postural stability. This effect of braces does not significantly compensate for the added mass in the second and third trimester.

Almost all studies on subjects suffering from a previous ankle sprain and chronic ankle instability show a positive effect of the ankle brace [Guskiewicz1996, Baier1998, Webster2017, Agres2019, Gregory2019, Cao2019] with the exception of [Friden1989]. However, the effect of ankle braces on postural stability of healthy subjects remains unclear, with studies showing a positive effect [Alt1999, Shaw2008, Barbanera2014, Dewar2019], no effect [Kinzey1997, Barboukis2002, Hardy2008, Gear2011, Willeford2018, Barbosa2019], or a negative effect [Calmels1991, Bennell1994, Henderson2019]. The effect of braces detected in this study on healthy young adults is combined with the effect of pregnancy mass gain, with the former counteracting the latter. As subjects respond to added mass by rigidifying their behavior, the ankle brace will directly support the strategy and allow subjects to relax muscles. As the sway increases, subjects are more reactive to perturbations and their postural stability increases.

4.3.3 Changes in frequency components of the CoP velocity

Beta ML is higher for Sports with ankle braces compared to without, which indicates a decrease of the high frequency components of the CoP velocity, indicating a decrease of the velocity and the sway, hence an increase of rigidity in the ML direction. The role of ankle braces is to add stiffness, especially in the ML direction, which leads to added rigidity and decreased sway velocity.

Interestingly, braces are the only factor affecting postural stability in the AP direction. Ankle braces mitigate the increase of Beta AP with pregnancy-induced mass gain. Beta AP is higher with ankle braces when not pregnant and for the first trimester and lower for the second and third trimesters. Mostly, ankle braces decrease the high frequency components of the CoP velocity before and at the beginning of the pregnancy and increase them towards the end of the pregnancy, leading to a constant measure of the high frequency component, so a sustained postural stability.

Finally, the index PF95 decreases with ankle braces, particularly in the first and second trimester, supposedly revealing an increase in postural stability with braces. Similarly to the effect detected by Log-MV AP, the effect of braces is weaker when the mass is higher, meaning the intervention struggles to counteract the decrease of postural stability resulting from pregnancy-induced mass gain. A decrease in PF95 indicates a reduction of the range of frequencies containing 95% of the CoP velocity power. This decrease in high frequency component is corroborated by the increase in Beta AP and ML, more noticeable at the beginning of the pregnancy.

4.4 Limitations

Results indicate a significant effect of the pregnancy-induced mass gain, isolated from any other factor related to pregnancy, such as ligament laxity. The aim of this study was not to simulate a pregnancy but to assess whether mass gain is a predominant factor in the decrease of postural stability. However, the response of the subjects to the mass gain is far from similar to the one a pregnant woman would present because of the time scale of our experiments. The mass gain during pregnancy occurs over 9 months and the pregnant body develops strategies to avoid continuous muscle contraction to maintain stance. Our subjects kept the mass on for 40 minute-sessions and could increase lower limb rigidity without reaching muscle fatigue.

The footwear conditions tried to evaluate a wide panel of footwear support and plantarflexion levels. However, the number of factors is too high. The study only compares one commercially available option in each category of flats, sports, low heels, and ankle brace. For example, a similar study comparing ankle braces of various stiffness from flexible to rigid, measuring the actual increase in ankle stiffness and in postural stability, would provide much more precise knowledge on the influence of ankle support. Finally, the relatively low number of subjects limits the statistical power of this study. Ten subjects allowed us to detect statistically significant effects but a higher number of subjects would lead to a more robust statistical analysis of the data. The statistical significance of the effects has been determined through ANOVAs. However, the significance of the difference between trimesters and footwear conditions has not been evaluated yet which prevent a deeper discussion of the results.

CHAPTER V

CONCLUSION AND FUTURE WORK

5.1 Conclusions

This study explored the effect of pregnancy-induced mass gain, including a change in inertia of the trunk, and the effect of footwear on postural stability. Twenty-two indices were computed from the CoP position measurements performed on 10 healthy young subjects. Some indices showed an effect of mass gain, footwear, or ankle brace. Briefly, results demonstrated a decrease in ML postural stability with mass gain and footwear such as heels. Ankle braces worn with sport shoes seem to increase postural stability, with a higher performance at the beginning of the simulated pregnancy than at the end. Contrary to most studies, the decrease in postural stability is detected by a decrease in postural sway, due to a tighter postural adjustment and a rigidification of the posture. Tighter postural adjustments may lead to an inefficient response to external perturbations, thus potentially increasing the risk of falling. This rigidification of the posture results from muscle contraction, which would lead to muscle fatigue if performed continuously during a pregnancy. Pregnant women develop alternative strategies to sustain postural stability throughout the pregnancy.

Our subjects, however, only have to carry the pregnancy-induced mass for sessions of about 40 minutes. Maintaining muscle contraction for the 5 minute-data acquisition periods was still comfortable and straightforward. So the protocol used here does not allow for the measurement of the body adaptation to the pregnancy-induced increase in mass and different types of footwear.

In conclusion, the study does detect that mass gain and footwear have an influence on the postural stability of healthy young female subjects, independently of all other pregnancy-induced physical, hormonal, and psychological changes. The influence of ankle support may be an interesting intervention to decrease the risk of falling of pregnant women.

5.2 Future Work

Many aspects of this study need to be detailed and further explored. First, further statistical analysis of the data is needed to determine the statistically significant differences between pregnancy stages and footwear conditions. In addition, since the subjects indicate a rigidification of the posture to maintain stability, analysis of the postural stability through time for each test session is necessary to determine a possible effect of muscle fatigue.

Second, the data acquisition also included motion analysis markers to determine the movements of the center of mass (CoM). This data needs to be processed in OpenSim to determine the position of the CoM at each time step. Numerous postural stability indices including the position of the CoM and the distance between the CoP and the projection of the CoM can then be computed and analyzed to provide a more detailed investigation of the postural stability.

As indicated in the discussion, one difficulty in studying the effect of footwear is the absence of standards for shoes and ankle supports. A more precise study of ankle braces and footwear with actual measurements of stiffness, plantarflexion, and proprioception would be extremely useful to determine which factors actually affect the postural stability.

This study also needs to be followed by a study of gait. Most pregnant women fall during gait and often carrying a load or walking on stairs. These situations are significantly more unstable that the quiet upright stance studied here.

Finally, although this study provides useful measurements on the influence of mass gain alone, a comprehensive study of the effect of the footwear and ankle support on postural stability of actual pregnant women is necessary before being able to conclude on the potential benefit of any training or intervention.

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APPENDICES

MATLAB codes to compute the 22 indices are presented below. The output of these codes is the index value for each subject at each stage and for each footwear condition.

<u>(1-2). Mean AP/ML</u>

This code has been used for both the AP and ML directions by changing the coordinates of the input.

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x= S(:,2,3);
                y= mean(x)

                %% save
                means{k,i,j} = [y];
                %fid = fopen('APmeans.txt','a');
                fid = fopen('MLmeans.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\t\n',k,i,j,y)
                fclose(fid);
            end
        end
    end
end
%save('APmeans','means')
save('MLmeans','means')
```

(3). Log-LNG

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x = S(:,1,3);
y = S(:,2,3);
A=[];
B=[];
C=[];
for ii = 1: numel(x)-1
    A(ii)= (x(ii+1)-x(ii))^2;
    B(ii)= (y(ii+1)-y(ii))^2;

end

  C= sqrt(A+B)';
  LNG= sum(C);
  LogLng= log(LNG);

                %% save
                LogLNG{k,i,j} = LogLng;

                fid = fopen('LogLNG.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,LogLng);
                fclose(fid);
            end
        end
    end
end
save('Loglng','LogLNG')
```

(4-5). Log-MV AP/ML

This code was used for both the direction AP and ML simultaneously and the output would have both values as two cell values in an array.

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
```

```
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x= S(:,1,3);
                y = S(:,2,3);
                fs = 100;
                T=1/fs;

%% Zero-mean operation
x = x - mean(x);
y = y - mean(y);

 %% Filtering
% Fourth-order zerophase-lag Butterworth filter
fc = 10;
[b,a] = butter(4,fc/(fs/2));
x = filtfilt(b,a,x);
y = filtfilt(b,a,y);

%% Calculation of velocity
% Five-point method finite difference
xv = NaN(length(x)-4,1); yv = xv;
for ii = 3:length(x)-2
    xv(ii-2) = (-x(ii+2) + 8*x(ii+1) - 8*x(ii-1) + x(ii-2))/(12/fs);
    yv(ii-2) = (-y(ii+2) + 8*y(ii+1) - 8*y(ii-1) + y(ii-2))/(12/fs);
end

%% Filtering the velocity
% Fourth-order zerophase-lag Butterworth filter
fc = 2.5;
[b,a] = butter(4,fc/(fs/2));
xv = filtfilt(b,a,xv);
yv = filtfilt(b,a,yv);

%% Calculation of log mean velocity
MeanVAP = mean(xv);
MeanVML = mean(yv);
LogMVAP = log(MeanVAP);
LogMVML = log(MeanVML);

                %% save
                LogMV{k,i,j} = [LogMVAP LogMVML];
                fid = fopen('Logmv.txt','a');

fprintf(fid,'%i\t%i\t%i\t%f\t%f\n',k,i,j,LogMVAP,LogMVML)
                fclose(fid);
             end
        end
    end
end
save('LogMeanV','LogMV')
```

(6). Angle

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y= COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
x = S(:,1,3);
y = S(:,2,3);
Fs = 100;
%% calculating covariance matrix of COP
MeanAP= mean(x);
MeanML= mean(y);
COPAP=[];
COPML=[];
COPX=[];
for jj = 1 : length(x)
COPAP(jj) = x(jj)-MeanAP;
COPML(jj) = y(jj)-MeanML;
end
COPX =[COPAP' COPML'];
A = cov(COPX(:,1),COPX(:,2));
%% Calculating the angle:

s11= A(1,1);
s12= A(1,2);
S21= A(2,1);
s22=A(2,2);

% Calculating the eigen values:
L1= (s11+s22+sqrt((s11-s22)^2+4*(s12)^2))/2;
L2= (s11+s22-sqrt((s11-s22)^2+4*(s12)^2))/2;

Angle= abs(atan(s12/(L2-s11)));

                %% save
                angle{k,i,j} = Angle;
                fid = fopen('Angles.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,Angle);
                fclose(fid);
            end
        end
    end
end
save('Angles','angle')
```

(7). Flattening

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y= COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
x = S(:,1,3);
y = S(:,2,3);
Fs = 100;
%% calculating covariance matrix of COP
MeanAP= mean(x);
MeanML= mean(y);
COPAP=[];
COPML=[];
COPX=[];
for jj = 1 : length(x)
COPAP(jj) = x(jj)-MeanAP;
COPML(jj) = y(jj)-MeanML;
end
COPX =[COPAP' COPML'];
A = cov(COPX(:,1),COPX(:,2));
%% Calculating the major and minor axes:

s11= A(1,1);
s12= A(1,2);
S21= A(2,1);
s22=A(2,2);

% Calculating the eigen values:
 L1= (s11+s22+sqrt((s11-s22)^2+4*(s12)^2))/2;
L2= (s11+s22-sqrt((s11-s22)^2+4*(s12)^2))/2;

alpha=0.95;

K=sqrt(-2*log(1-alpha));

% Calculating the length of major and minor axes:
 Long=K*sqrt(L1);
Short=K*sqrt(L2);

% Calculation of flattening value:
 FlatteningV= 1-(Short/Long);
```

```
                %% save
                Flatteningindex{k,i,j} = FlatteningV;
                fid = fopen('Flattening.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,FlatteningV);
                fclose(fid);
            end
        end
    end
end
save('FLATTENING','Flatteningindex')
```

(8). MP3

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x=S(:,1,3);
y=S(:,2,3);

% plot statokinesigram
figure(1); clf; hold on;
plot(x,y)
title('statokinesigram')

% sway density computation
fs = 100;
R = 3;
N = numel(x);
density = zeros(N,1);

for c = 1:N
    for b = c:-1:2
        a = sqrt((x(c)-x(b-1))^2 + (y(c)-y(b-1))^2);
        if a <= R
            density(c) = density(c) + 1;
        else
            break
        end
    end
    for b = c:N-1
        a = sqrt((x(c)-x(b+1))^2 + (y(c)-y(b+1))^2);
        if a <= R
```

```
            density(c) = density(c) + 1;
        else
            break
        end
    end
end

density = density/fs;
%[G,H]=butter(2,1)
density = lowpass(density,12.5,fs);

figure(2); clf; hold on;
plot(1:N,density)

%% moving average smoothing:
time= 1:N;
s=20;
p=length(density);
q=zeros(1,p-s);
for t=1:p-s
    q(t) = mean(density(t:t+s));
end

figure(3);clf; hold on
plot(1:N,density)
plot(time(1:length(q)),q);

%% find peaks in function
[pks,locs] = findpeaks(q);

figure(4); clf; hold on
plot(1:length(q),q)
plot(locs,q(locs),'*k')

mp= mean(pks)
                %% save
                meanpeaks{k,i,j} = mp;
                fid = fopen('Meanpeaks.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,mp)
                fclose(fid);
            end
        end
    end
end
save('Meanpeaks','meanpeaks')
```

(9). Log-Slope-MP

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
```

```
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x = S(:,1,3);
                y = S(:,2,3);
                % Trial length (s)
                tlength = floor(length(x)/(60*fs))*60;
% Acquisition frequency (Hz)
fs = 100;

%% ***** Filter the statokinesigram *****
 % Filter the statokinesigram: fourth-order zerophase-lag Butterworth
filter
fc = 10;
[b,a] = butter(4,fc/(fs/2));
x = filtfilt(b,a,x);
y = filtfilt(b,a,y);

 %% ***** Compute the sway density *****
 filt=[];
N = length(x);
density = zeros(N,5);
means = [];
MP = [];
for r = 1:5
a=[];
for ii = 1:N
    for jj = ii:-1:2
        a = sqrt((x(ii)-x(jj-1))^2 + (y(ii)-y(jj-1))^2);
        if a <= r
            density(ii,r) = density(ii,r) + 1;
        else
            break
        end

    end
    for jj = ii:N-1
        a = sqrt((x(ii)-x(jj+1))^2 + (y(ii)-y(jj+1))^2);
        if a <= r
            density(ii,r) = density(ii,r) + 1;
        else
            break

        end
    end
end


density(:,r) = density(:,r)/fs;
end
% Filter the sway density
fc = 2.5;
[b,a] = butter(4,fc/(fs/2));
```

```
filt = filter(b,a,density);


%% ***** Find peaks for R (1,5) *****
for r = 1:5

[pks,locs] = findpeaks(filt(:,r));

means = mean(pks);
MP(r) = means ;

end

aa= 2:1:5;
subplot(2,1,1)
plot(aa,MP(2:5));
p = polyfit(aa,MP(2:5),1);
subplot(2,1,2)
plot(aa,polyval(p,aa),'k-');
LogslopeMP = log(p(1));

                 %% save
                LslopeMP{k,i,j} = LogslopeMP ;
                fid = fopen('LogSMP.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,LogslopeMP);
                fclose(fid);
            end
        end
    end
end
save('LogSlopeMP','LslopeMP')
```

<u>(10-11). Zero-Cross-V-AP/ML</u>

This code was used for both AP and ML directions simultaneously.

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
time = 60;

 %% Load the data

                S = Y.(fn{j});
                x= S(:,1,3);
                y= S(:,2,3);
```

```
                fs=100;

%% Zero-mean operation
x = x - mean(x);
y = y - mean(y);

%% Filtering
% Fourth-order zerophase-lag Butterworth filter
fc = 10;
[b,a] = butter(4,fc/(fs/2));
x = filtfilt(b,a,x);
y = filtfilt(b,a,y);

%% Calculation of velocity
% Five-point method finite difference
xv = NaN(length(x)-4,1); yv = xv;
for ii = 3:length(x)-2
    xv(ii-2) = (-x(ii+2) + 8*x(ii+1) - 8*x(ii-1) + x(ii-2))/(12/fs);
    yv(ii-2) = (-y(ii+2) + 8*y(ii+1) - 8*y(ii-1) + y(ii-2))/(12/fs);
end

%% Filtering the velocity
% Fourth-order zerophase-lag Butterworth filter
fc = 2.5;
[b,a] = butter(4,fc/(fs/2));
xv = filtfilt(b,a,xv);
yv = filtfilt(b,a,yv);

%% ***** Compute Zero-cross-V *****
% Compute the number of zero crosses of low-pass filtered CoP velocity
nx = xv(1:time*fs-1).*xv(2:time*fs);
tmp = find(nx < 0);
nx = length(find(nx < 0));
ny = yv(1:time*fs-1).*yv(2:time*fs);
ny = length(find(ny < 0));

ZerocrossV = [nx ny];

                %% save
                ZeroCVAP{k,i,j} = [ZerocrossV(1)];
                fid = fopen('ZCVAP.txt','a');

fprintf(fid,'%i\t%i\t%i\t%f\t%f\n',k,i,j,ZerocrossV(1),ZerocrossV(2))
                fclose(fid);
                ZeroCVML{k,i,j} = [ZerocrossV(2)];
                fid = fopen('ZCVML.txt','a');

fprintf(fid,'%i\t%i\t%i\t%f\t%f\n',k,i,j,ZerocrossV(1),ZerocrossV(2))
                fclose(fid);
            end
        end
    end
end
save('ZCVAP','ZeroCVAP')
save('ZCVML','ZeroCVML')
```

(12-15). Log-Alpha AP/ML and Beta AP/ML

This code computes the values of Log-Alpha and Beta. It was also used for both the directions AP and ML simultaneously and the output would have both the directions as two cell values in an array.

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});

 %% Load the data
S = Y.(fn{j});
x = S(:,1,3);
y = S(:,2,3);
fs = 100;

%% Figure inputs
% Font for figures
ft = 'Arial';
% Fontsize for figures
fs0 = 20;
% Screen size
scrsz = get(0,'ScreenSize');

% Duration (s) used to compute the number of zero-crossings
time = 60;

%% Zero-mean operation
x = x - mean(x);
y = y - mean(y);

%% Filtering
% Fourth-order zerophase-lag Butterworth filter
fc = 10;
[b,a] = butter(4,fc/(fs/2));
x = filtfilt(b,a,x);
y = filtfilt(b,a,y);

%% Calculation of velocity
% Five-point method finite difference
xv = NaN(length(x)-4,1); yv = xv;
for ii = 3:length(x)-2
    xv(ii-2) = (-x(ii+2) + 8*x(ii+1) - 8*x(ii-1) + x(ii-2))/(12/fs);
    yv(ii-2) = (-y(ii+2) + 8*y(ii+1) - 8*y(ii-1) + y(ii-2))/(12/fs);
```

```
end

%% ***** Compute Zero-cross-intervals *****
% Compute the number of zero-cross-intervals
nx = xv(1:time*fs-1).*xv(2:time*fs);
tmp1 = find(nx < 0);
% AP
intervalAP = NaN(length(tmp1)-1,1);
for ii = 2:length(tmp1)
    intervalAP(ii-1) = tmp1(ii) - tmp1(ii-1);
end
% ML
ny = yv(1:time*fs-1).*yv(2:time*fs);
tmp2 = find(ny < 0);
intervalML = NaN(length(tmp2)-1,1);
for ii = 2:length(tmp2)
    intervalML(ii-1) = tmp2(ii) - tmp2(ii-1);
end

%% Gamma Distribution of inter zero cross intervals
pdx = gamfit(intervalAP);
pdy = gamfit(intervalML);

% Plot velocity curve and Gamma distribution
figure(1)
set(figure(1),'Position',[1/10*scrsz(3) 1/10*scrsz(4) ...
    12/10*scrsz(4) 6/10*scrsz(4)]);
clf;
% Velocity profile
subplot(2,1,1); hold on; set(gcf,'Color','w');
xlabel('Time (s)');
ylabel('COP velocity_{AP} (m/s)');
axes_handle = get(gcf,'CurrentAxes');
set(axes_handle,'FontName',ft,'FontSize',fs0);
set(axes_handle,'XLim',[0 time]);
plot((1:length(xv))/fs,xv,'b-');
% plot((1:length(xv))/fs,yv,'b-');
yr = get(axes_handle,'Ylim');
for ii = 1:length(tmp1)
    plot(tmp1(ii)/fs*ones(1,2),yr,'r-');
end
% Gamma distribution
subplot(2,1,2);
hold on; set(gcf,'Color','w');
xlabel('Time interval (s)');
ylabel('Frequency');
axes_handle = get(gcf,'CurrentAxes');
set(axes_handle,'FontName',ft,'FontSize',fs0);
histogram(intervalAP);
N = histcounts(intervalAP);
% histogram(intervalML);
% N = histcounts(intervalML);
xt = get(axes_handle,'XTick');
set(axes_handle,'XTickLabel',xt/fs);
plot(0:xt(end),sum(N)*gampdf(0:xt(end),pdx(1),pdx(2)),'r-
','LineWidth',2);
```

```
% plot(0:xt(end),sum(N)*gampdf(0:xt(end),pdy(1),pdy(2)),'r-
','LineWidth',2);

%% Saving log alpha and Beta values
logAlphaAP = log(pdx(1));
BetaAP = pdx(2);

logAlphaML = log(pdy(1));
BetaML = pdy(2);

                %% save
                LogAlpha{k,i,j} = [logAlphaAP logAlphaML];
                fid1 = fopen('LogAlpha.txt','a');

fprintf(fid1,'%i\t%i\t%i\t%f\t%f\n',k,i,j,logAlphaAP,logAlphaML);
                fclose(fid1);
                Beta{k,i,j} = [BetaAP BetaML];
                fid2 = fopen('Beta.txt','a');

fprintf(fid2,'%i\t%i\t%i\t%f\t%f\n',k,i,j,BetaAP,BetaML);
                fclose(fid2);
            end
        end
    end
end
save('Logalpha','LogAlpha')
save('beta','Beta')
```

Frequency domain indices are based on the CoP power spectral density (PSD) functions, computed by Fast Fourier Transform of the CoP path, or the CoP position in the AP/ML directions.

(16). Log-Power

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x = S(:,1,3);
                y = S(:,2,3);
                N = length(x);
                Fs = 100;
n = 2^nextpow2(N);  % Next power of 2 from length of x
fFFT = Fs*linspace(0,1,n);
```

```
xdftt = fft(x,n)/(1/Fs*N);
xdft = xdftt(1:n/2+1);
psdx =  abs(xdft).^2;
[PSDMat,W] = periodogram(x,1:length(x),length(fFFT));

fff = W/pi*Fs*0.5;
f= find(fff>0.15 & fff<5);
count = 0;
Power = [];
for ii = f(1):20:f(end)
    count = count + 1;
    Power(count) = fff(ii)*PSDMat(ii)*20;
end

% Plot the power curve
figure(1)
clf; hold on;
plot(f(1:20:end),Power,'b-');

% Calculating the log of Power
Power1 = sum(Power);
LogPower = log(Power1);


                %% save
                LPower{k,i,j} = LogPower ;
                fid = fopen('LogPower.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,LogPower);
                fclose(fid);
            end
        end
    end
end
 save('LOGpower','LPower')
```

(17). PF50

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x = S(:,1,3);
                y = S(:,2,3);
               Fs = 100;
N = length(x);
```

```
n = 2^nextpow2(N);  % Next power of 2 from length of x
fFFT = Fs*linspace(0,1,n);
xdftt = fft(x,n)/(1/Fs*N);
xdft = xdftt(1:n/2+1);
psdx =  abs(xdft).^2;
[PSDMat,W] = periodogram(x,1:length(x),length(fFFT));

fff = W/pi*Fs*0.5;
f= find(fff>0.15 & fff<5);
count = 0;
Power = [];
for ii = f(1):20:f(end)
    count = count + 1;
    Power(count) = fff(ii)*PSDMat(ii)*20;
end

% Plot the power curve
figure(1)
clf; hold on;
plot(f(1:20:end),Power,'b-');

% Calculating PF-50
Power1=sum(Power);
Power50=0.50*Power1;

sumpower = 0;
for kk=1:length(Power)
    sumpower=sumpower+Power(kk);
    if sumpower<=Power50
    w=kk;
    else
        continue
    end
end
P50=w*20;

                %% save
                PowerF50{k,i,j} = P50 ;
                fid = fopen('PF50.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,P50);
                fclose(fid);
            end
        end
    end
end
save('PF50','PowerF50')
```

(18). PF95

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
```

```
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x = S(:,1,3);
                y = S(:,2,3);
                Fs = 100;
N = length(x);
n = 2^nextpow2(N);  % Next power of 2 from length of x
fFFT = Fs*linspace(0,1,n);
xdftt = fft(x,n)/(1/Fs*N);
xdft = xdftt(1:n/2+1);
psdx =  abs(xdft).^2;
[PSDMat,W] = periodogram(x,1:length(x),length(fFFT));

fff = W/pi*Fs*0.5;
f= find(fff>0.15 & fff<5);
count = 0;
Power = [];
for ii = f(1):20:f(end)
    count = count + 1;
    Power(count) = fff(ii)*PSDMat(ii)*20;
end

% Plot the power curve
figure(1)
clf; hold on;
plot(f(1:20:end),Power,'b-');

% Calculating PF-50
Power1=sum(Power);
Power95=0.95*Power1;

sumpower = 0;
for jj=1:length(Power)
    sumpower=sumpower+Power(jj);
    if sumpower<=Power95
    u=jj;
    else
        continue
    end
end

P95 = u*20;

                %% save
                PowerF95{k,i,j} = P95 ;
                fid = fopen('PF95.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\n',k,i,j,P95);
                fclose(fid);
            end
        end
    end
```

```
end
save('PF95','PowerF95')
```

(19-22). Slopes of the PSD

This code computes all the values of slopes of PSD in one run. It was also used for the AP and ML directions simultaneously and the output would have both the directions as two separate arrays with two cell values for low-frequency and high-frequency.

```
myFolder ='../../Pregnancy/Results/COPPositions/';
theFiles = dir(fullfile(myFolder,'*mat'));
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', baseFileName);
    load(fullFileName);
    for i = 1 : 5
        fprintf(1, 'Pregnancy Stage: %i\n',i);
        Y=COP{i};
        fn= fieldnames(Y);
        for j = 1 : numel(fn)
            if ~isempty(Y.(fn{j}))
                fprintf(1, 'Footwear type: %s\n', fn{j});
                S = Y.(fn{j});
                x= S(:,1,3);
                Fs=100;
                N = length(x);
                n = 2^nextpow2(N);  % Next power of 2 from length of x
                fFFT = Fs*linspace(0,1,n);
                xdftt = fft(x,n)/(1/Fs*N);
                xdft = xdftt(1:n/2+1);
                psdx =  abs(xdft).^2;

                [PSDMat,W] = periodogram(x,1:length(x),length(fFFT));
                fff = W/pi*Fs*0.5;
                ff = fff(1:length(fff)/2+1);
                figure(1); clf;
                loglog(fff,PSDMat)
                hold on
                loglog(fFFT(1:n/2+1),psdx)
                grid on
                title('PSD Using FFT')
                xlabel('Frequency (Hz)')
                ylabel('Power/Frequency (mm^2/Hz)')

                %% First slope - low frequency 0.04-0.5 Hz
                [~,ind1] = min(abs(ff-0.5));
                aa = log10(fFFT(5:ind1));
                bb = log10(psdx(5:ind1))';

                figure(2); clf; hold on;
                plot(aa,bb,'.-')
                p1 = polyfit(aa,bb,1);
                plot(aa,polyval(p1,aa),'r-')
```

```
                %% second slope - high frequency 0.5-1 Hz
                clear aa bb
                ff = fFFT(1:n/2+1);
                [~,ind5] = min(abs(ff-1));
                aa = log10(ff(ind1:ind5));
                bb = log10(psdx(ind1:ind5))';

                figure(2);
                plot(aa,bb,'.-')
                p2 = polyfit(aa,bb,1);
                plot(aa,polyval(p2,aa),'k-')

                %% save
                slopes{k,i,j} = [p1(1) p2(1)];
                fid = fopen('APslopes.txt','a');
                %fid = fopen('MLslopes.txt','a');
                fprintf(fid,'%i\t%i\t%i\t%f\t%f\n',k,i,j,p1(1),p2(1))
                fclose(fid);
            end
        end
    end
end
save('APslopes','slopes')
% save('MLslopes','slopes')
```

VITA

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