PARAMETER IDENTIFICATION OF BIOMECHANICAL MODEL USING MEASURED VIBRATION RESPONSE TO WALKING GENERATED EXCITATIONS WITH OPTIMIZATION

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

Parameter Identification of Biomechanical Model Using Measured Vibration Response to Walking Generated Excitations with Optimization

Ahmed Atia

Normal birth is defined as when a child is born between 37 and 42 completed weeks of pregnancy. If the child is born before 37 weeks of pregnancy, the birth is considered preterm. The causes of preterm births are still not understood properly and research is being carried out to identify the causes and to prevent preterm birth. Preterm birth has serious effects on preterm children. The child born preterm is prone to defective physical growth and also subject to poor psychological growth. Preterm birth is associated with deterioration in the cervical resistance. Cervical fatigue may be caused by static loads during extended periods of standing, dynamic loads while working which involve a lot of moving around and walking, or impulse loads caused by sudden jerky movements.

The present study is concerned with developing biomechanical models of the pregnant woman in order to study the biomechanical behavior of the pregnant woman under different types of loads. Previously developed 3-Degree of Freedom and 5-Degree of Freedom models are used to obtain the response of the pregnant woman to vertical vibration, and also to predict the

cervical loads in the seated position. A 9-Degree of Freedom model is developed in this study in order to obtain the response of the woman's body to walking generated excitation, and to predict the cervical loads.

Results from the 3 developed models are obtained at two different conditions, preterm "exactly at 37 weeks of pregnancy" and term "exactly at 42 weeks of pregnancy" conditions. The results from the 2 seated models are compared to the results obtained from the 9-Degree of Freedom walking model, in terms of cervical loads. The comparison shows that the cervical loads are higher in the walking position. Therefore, it is decided to identify the parameters of the walking model. The model consists of 7-Degree of Freedom for the woman's body and 2-Degree of Freedom for the fetus and the uterus combination. As identifying all the 9 parameters of a 9-DOF pregnant woman through measurements is extremely difficult, it is decided that the identification process will take place on the 7-Degree of Freedom model. To identify such a model, experimental measurements are carried out on a walking individual. The error between the computed and experimental results is minimized using genetic algorithm. Parameters of the 7-Degree of Freedom model are identified through the optimization process. After identifying the 7-Degree of Freedom model parameters, the other 2-Degree of Freedom are added.

The optimized biomechanical model is used to obtain the response of the pregnant mother to dynamic environmental loads that the pregnant woman is normally subjected to during her daily activities. The results are presented and discussed, in order to get a better understanding of the loads bearing on the cervix. The results show that there is not much difference between the experimented model and the nominal model.

Dedication

To my ***parents***, my ***family***, especially my sisters, ***Marwa*** and ***Maha***, and to my beloved wife ***Amy***.

ACKNOWLEDGMENT

First of All, I want to give my sincere Thanks to **ALLAH** for all the blessings I have been given in my life.

Completing my Master Degree is probably the most remarkable time throughout my years of education. The best and worst memories of my Master's journey have been shared with many people. It has been a privilege to spend the years of my Master's surrounded by such wonderful persons.

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My affectionate thanks to my family. ***My Father, My Mother, and My Sisters*** who have been supportive to me throughout my life. And my special thanks to ***my wife Amy*** for giving me continuous support.

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List of Symbols

Symbol	Description
[C]	Damping Matrix
[K]	Stiffness Matrix
[M]	Mass Matrix
$\{\ddot{x}\}$	Output Acceleration
$\{\dot{x}\}$	Output Velocity
$\{x\}$	Output Displacement
{F}	Force Vector
AP	Apparent Mass
$C_i(f)$	Computed Data Transfer Function
DMP	Driving Point Mechanical Impedance
DOF	Degree of Freedom
DVS	Design Variables
$E_i(f)$	Experimental Data Transfer Function
EMG	Electromyography
$Er(x)$	Error Function

EUROPOP	European Programme of Occupational Risks and Pregnancy Outcome
FD	Frequency Domain
F_c	Dynamic Load on the Cervix
FFT	Fast Fourier Transform
F_s	Static Load on the Cervix
g	Gravity Acceleration (9.81 m/s^2)
GA	Genetic Algorithm
LDH	Lactate Dehydrogenase
LPS	Lipopolysaccharide
M-DOF	Multi Degree of Freedom
STH	Seat to Head
ω	Natural Frequency
x(t)	Input Deflection of the 3-DOF model
y(t)	Input Deflection

Chapter 1. Introduction

Preterm birth is a serious concern as it is the second largest direct cause of childhood death for children under the age of five. One of the latest studies reports that the year 2010 had 14.9 million cases of preterm birth [1][2]. The total number of births for 2010 is 135 million. More than 11.1% of the babies born in 2010 were born preterm. And it is the leading cause of newborn death (babies in the first four weeks of their life) [5].

Reportedly, there are several studies that investigate the causes and the reasons behind preterm birth. Yet, the causes are still elusive [11][12]. There are many studies that focus on the survival of the preterm babies. More than three-quarters of preterm babies can be saved, but with disabilities to some degree [5]. The disabilities can be physical, mental or both.

A wide range of the studies concerned with preterm birth are reported. Some studies try to predict the occurrence of preterm birth, while others try to identify the risk factors that may cause it. Most of the studies try to investigate the problem from a medical point of view, yet some recent studies try to look at the problem from a biomechanical point of view.

Some of the previous studies dealt with the relation between cervical load and preterm birth [33][37]. The biomechanical properties of pregnant women are modeled in a sitting position [37], to study the behavior of pregnant woman in terms of natural frequency and vibration transmissibility. It is believed that vibrations in the vertical direction induce loads on the cervix. The loads on the cervix include static load, because of the weight of the fetus and the amniotic fluid, and dynamic load that is caused by movements or daily activities.

In the next chapter, the scope of this research is presented, with a definition of the problem of preterm birth, some statistics and facts, and some of the methods of treatment. This will be followed by a literature survey which covers three major points: the investigations of preterm birth, modeling the human body under whole body vibrations, and the analysis of human walking mechanics. Finally, a set of objectives is presented along with the details of the thesis organization.

Chapter 2. Scope, Literature Review, and Objectives

2.1. Introduction

It is estimated that annually, 15 million babies are born preterm. It is also believed that this number is increasing [5]. One million babies are estimated to die annually out of the 15 million born preterm. Preterm birth is the leading cause of new born deaths and the second cause of deaths in children under five. Preterm birth is a serious problem according to studies and statistics.

In this chapter, a scope of preterm birth is presented, showing the risks caused by preterm birth and the serious problems that accompany preterm born babies. Preterm birth is defined and statistical information is shown. Certain studies show some methods of prevention of preterm birth.

A literature survey is presented, which covers three points: preterm studies, biomechanical modeling and walking excitation experiments. The objectives of the present study are presented along with the thesis organization.

2.2. Scope

Preterm birth is the second largest direct cause of infants death in children younger than 5 years [1]. Complications due to preterm birth are estimated to be responsible for 35% of the world's annual neonatal death [1][2]. Preterm birth also increases the risk of death due to other causes, especially from neonatal infections [1][2][3]. The chances of survival for premature infants are very low, and the vast majority of the infants are disabled to some degree. The disabilities can be mental, physical or both.

Despite the advances in technology and medical knowledge, the causes of preterm birth still remain elusive. Therefore, many studies focus on explaining the reason behind preterm birth, while others work on developing methods to prevent it.

2.2.1. Definition of the Problem

According to the World Health Organization [5], preterm birth is defined as any birth before 37 completed weeks of gestation, or fewer than 259 days after the mother's last menstruation [1][5].

	Gestational age	Proportion of all <37 weeks (%, 95% CI)
Extremely preterm	<28 weeks	5·2% (5·1–5·3)
Very preterm	28–<32 weeks	10·4% (10·3–10·5)
Moderate or late preterm	32–<37 weeks	84·3% (84·1–84·5)

Figure 1: Distribution of Preterm according to gestational age [1]

These 37 weeks can be further subdivided based on gestational age: extremely preterm (<28 weeks), very preterm (28–<32 weeks) and moderate or late preterm (32–<37 completed weeks of gestation), as shown in Figure 1.

Preterm can be classified into two groups: (1) spontaneous preterm birth and (2) provider-initiated preterm birth. Spontaneous preterm birth is a result of many factors causing the uterus to change from quiescent to active contractions before 37 completed weeks of gestation. However, the exact reason of spontaneous preterm birth is undefined [1][7]. Yet, some factors can increase the risk of spontaneous preterm birth, including young or old maternal age, short interpregnancy intervals, low maternal Body Mass-Index, multiple pregnancies, diseases of pregnancy and infections [1][9][10].

Provider-initiated preterm birth is defined as intervention in labor or cesarean section before 37 completed weeks of gestation, for fetal indications or other non-medical reasons [1][5]. Generally, countries with high levels of preterm births have very low incidences of provider-initiated preterm birth. Many high and middle income countries have an increasing rate of provider-initiated preterm births and recent data shows that 872 provider-initiated preterm births between 34–36 weeks had taken place in the United States, of which most were done in the absence of good medical indication [1][7].

2.2.2. Statistics and Facts

Recent studies focus on finding certain or estimated facts about the numbers of preterm births around the world. One of the studies shows the number of preterm births in 2010 with the time trend since 1990 [1]. Based on 184 countries, the global average for preterm births in 2010 is 11.1% (uncertainty range 9.1–13.4%). The regions with the highest preterm birth rate in 2010 are: Southeastern Asia, South Asia, and sub-Saharan Africa. More than 60% of all preterm births are estimated to be concentrated in South Asia and sub-Saharan Africa where 9.1 million live births were estimated to be preterm in 2010.

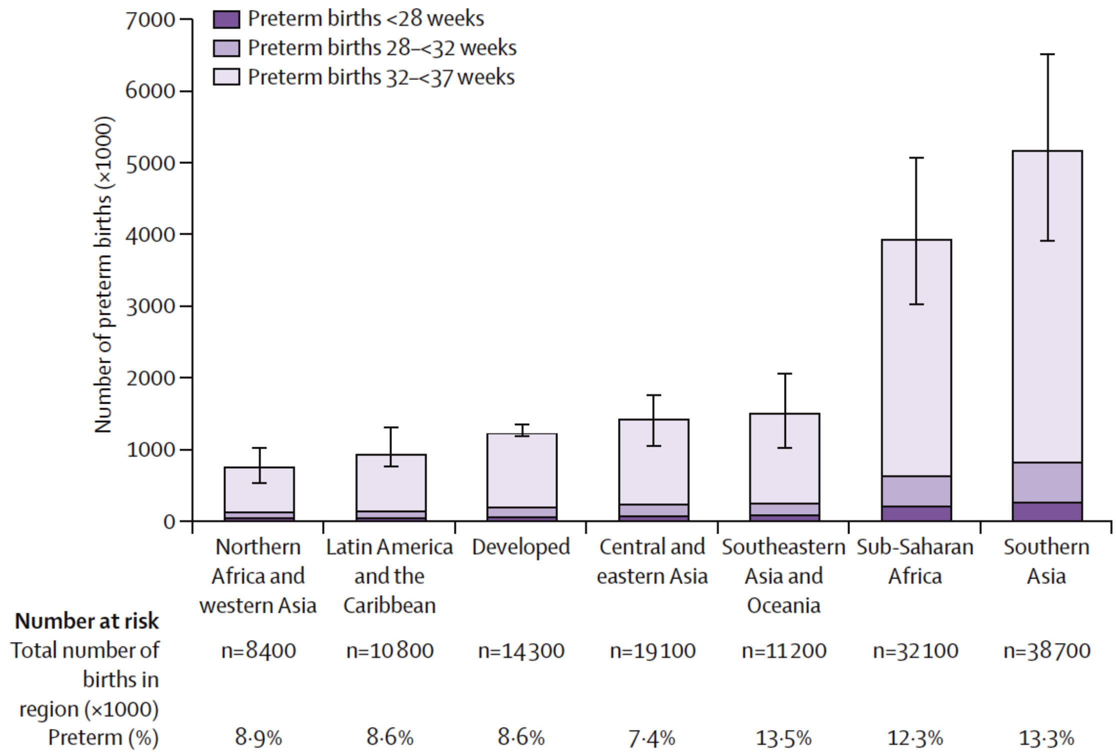

Figure 2: The estimated preterm births by region and by gestational age grouping for the year 2010 [1]

Figure 2 shows the estimated preterm births by region and by gestational age grouping for the year 2010 [1]. At a national level, the preterm birth rate in several Northern European countries ranges around 5%. It is found that India is the country with the highest number of preterm births for 2010, with 3,519,118 preterm births (23.6% of global total) out of 27,200,000 live births (20.1% of global total). China follows, with 1,172,259 preterm births (7.8% of global total) out of 16,600,000 live births (12.3% of global total) in 2010. Nigeria comes in 3rd rank, with 773,597 preterm births (5.2% of global total) out of 6,332,251 live births (4.7% of global total). Pakistan comes in 4threank with 748,142 preterm births (5% of global total) out of 4,741,460 live births (3.5% of global total), followed by Indonesia, in the 5th rank with 675,744 preterm births (4.5% of global total), out of 4,371,818 live births (3.2% of global total). USA is found to have 517,443 preterm births

(3.5% of global total) out of 4,300,620 live births for the year 2010 (3.2% of global total). Canada has a mean percentage of preterm births of about 5% for the year 2010. The total number of preterm births around the world in the year 2010 is found to be 14.9 million out of 135 million live births. The preterm births are found to be over 11.1% of the live births, which has led to the ongoing search for a cure or solution to prevent this problem.

2.2.3. Methods of Treatment

The numbers show that preterm birth is a serious concern. Efforts primarily aim to improve the survival of preterm babies. Yet, such efforts do not prevent the occurrence of preterm birth [11][13].

The treatment methods of preterm birth work in two ways. The first way is by raising awareness of the preterm problem before pregnancy. The second way is during pregnancy, by raising awareness among pregnant women.

2.2.3.1. Pre-pregnancy awareness

Raising public awareness of the problem of preterm birth and its major effects on childhood death, as the second largest direct cause of childhood death in children under the age of five, is believed to reduce avoidable risk factors including repeated surgical abortions. Many countries have established new rules regarding pregnant women at work, which aim to protect the mother from risks that may lead to preterm birth. The EUROPOP study shows that preterm birth has no relation to the type of work. However, it is related to prolonged standing (> 6 hours a day) or prolonged work (> 42 hours a week) [11][14]. Quitting smoking is also believed to protect pregnant women and their children [11][14].

2.2.3.2. During Pregnancy

Not all methods can be introduced before pregnancy, but some can be introduced during pregnancy, including quitting smoking, taking vitamins and practicing healthy nutrition [11]. One of the treatments during pregnancy is screening for asymptomatic bacteria, followed by healthy treatment in order to reduce the risk of preterm birth [11][15]. Some studies tried to determine if other types of screening in low risk-women followed by appropriate treatment are beneficial, including: screening for Ureaplasma Urealyticum, group B streptococcus, Trichomonas Vaginalis [11][13]. Routine ultra sound scanning during pregnancy of the length of the cervix can help identify risky pregnancies [11][13]. Self-care is also believed to reduce the risk of preterm birth. Self-care methods include appropriate nutrition, proper medical care, avoiding stress, avoiding infections, and the control of preterm birth risk factors (e.g. working for long hours standing on the feet) [11][16][17].

2.3. Literature Review

A thorough review of the literature is carried out in order to search for studies that are concerned with preterm birth. The literature in this study focuses on three points: preterm studies, modeling the human body under whole body vibrations, and the analysis of human walking mechanics in order to identify the biodynamic parameters.

2.3.1. Preterm Studies

Preterm birth is of a serious concern. Most of the studies focus on the prediction of preterm birth and the risk factors, while other studies focus on the survival chances of preterm born babies. In 2000, Goldenberg et al. studied the relation between plasma granulocyte colony-stimulating factor and subsequent spontaneous preterm birth in pregnant women without symptoms. The study found that elevated plasma granulocyte colony-stimulating factor levels are associated with subsequent spontaneous preterm birth [18]. Goldenberg also studied the traditional risk factors and new markers for preterm birth derived from the preterm prediction study and found that regardless of other risk factors, a short cervix predicts a subsequent positive fetal fibronectin result, which predicts subsequent cervical shortening [18]. In 2001, Verdenik et al. tried to estimate the risk of preterm birth in women admitted to the tertiary maternity hospital for preterm contractions by measuring electrical uterine activity. They proposed uterine EMG as a simple, non-invasive means to estimate the risk of preterm birth in a high-risk population with multiple risk factors present [19]. Coleman et al. presented a comparison of cervicovaginal interleukin (IL)-1β, IL-6 and IL-8 with fetal fibronectin and cervical dilatation in the prediction of preterm delivery, and they found that the measurement of cervicovaginal cytokines has limited ability to predict imminent delivery [20]. Some of the preterm studies were done on animals. In 2002, Celik and Ayar investigated the effects of erythromycin on pregnancy duration and on live birth weight in lipopolysaccharide (LPS)-induced preterm labor model in rats. The data obtained from this study shows that erythromycin caused prolongation of the pregnancy period and increased live birth weight in LPS-induced preterm labor of pregnant rats [21]. Other studies are done to investigate the risk of preterm birth among certain regions or certain groups of people. Dafopoulos et al. [22] examined the effect of short interpregnancy intervals on the occurrence of preterm birth in two ethnically different Greek populations. The study showed that short interpregnancy intervals seems to be a risk factor in the population of rural, Romany, Muslim women [22]. Subtila et al. took a case control study to study the relation between preterm birth and bacterial vaginosis to determine whether it modifies the risk of preterm birth, and they found that bacterial vaginosis is associated with preterm birth. Nonetheless, it does not appear to predict preterm birth among the patients of the case study [23]. In 2003, Madazli et al. compared angiogenin, lactate dehydrogenase (LDH) and fibronectin levels in mid-trimester amniotic fluid of women with preterm and term births to find their predictive values for preterm birth. They found that second trimester angiogenin is found to be quite effective in the prediction of preterm birth [24]. Medda et al. tried to determine whether genetic amniocentesis is a risk factor for preterm birth or not, and their study showed a relation between genetic amniocentesis and preterm birth [25]. In 2004, Krymko et al. aimed to identify the risk factors for recurrent preterm birth, and they concluded that when adjusted for variables, short intervals between pregnancies is an independent risk factor for recurrent preterm birth [26]. In 2006, Vogel et al. examined serum relaxin as a predictor of spontaneous preterm birth [27]. They found that serum relaxin levels decrease less rapidly in women who subsequently deliver preterm [27]. Kurata et al. took a case control study to identify risk factors of preterm birth at less than 35 weeks in patients with renal transplant, and their case study related hypertension prior to pregnancy, proteinuria and serum creatinine to the occurrence of preterm birth [28]. In 2009, Smith et al. presented a review of the published literature to identify and appraise published reviews on five main interventions for preventing and treating preterm birth, which are: antibiotic therapy, cervical cerclage, progesterone therapy, bed rest, and tocolytic therapy [29]. The author of this review concluded that “there is no evidence either supporting or refuting” the use of bed rest as an intervention to prevent preterm birth [29]. Cervical cerclage assumes that preterm birth is due to a week cervix and puts stitches on the cervix in order to reduce pressure on the cervix. In 2011, Wisanskoonwong, Fahy, and Hastie reviewed the research literature to study how effective are the medical interventions that aim to reduce the rates of preterm births [30]. This review showed that medical interventions aimed at preventing, not just delaying, preterm birth are not effective at a population level [30]. In 2012, Schaaf et al developed a prognostic model for predicting spontaneous singleton preterm birth. The model's discrimination was fair and it had modest calibration [31].

The vast majority of the reported studies on preterm birth focus on the risk factors influencing preterm birth. Yet, not all factors are discovered. More investigation is needed.

2.3.2. Biomechanical Modeling

Biomechanical models have been used in order to study the behavior of humans under a variety of dynamic environmental conditions. Several models have been used depending on the type of input and what part of the body has been focused on in the study.

In 1993, Qassem, Othman, and Abdul-Majeed developed a new biomechanical model to study the effect of vertical and horizontal vibrations [32]. In their study the vibration force comes from hand, seat, or both. They stated that the body segments presented in the model are affected by horizontal vibration when the input force comes from both hand and seat more than when it comes from the seat alone. They stated that the head is affected by vertical vibrations when the force comes from the seat more than when it comes from both hand and seat. In 1995, Qassem and Othman studied the effect of vibration on sitting pregnant woman [73]. They presented an electrical simulation of a 60 Kg pregnant woman subjected to horizontal and vertical vibrations. The results from their study showed that the mechanical vibrations affect the body segments differently based on their location. They also showed that the female driver is affected more than the female passenger.

In 2001, Bhat and Bhat [33] developed a 3-DOF model to examine the static and dynamic load on the cervix of a pregnant mother. The study indicates the need for extreme caution warranted in the case of high risk pregnancies in a highly dynamic environment [33]. In 2005, T-H Kim et al. developed a biomechanical model of the human body in sitting posture to study vibration transmissibility in vertical direction [34]. They tried to find an appropriate structure of a human model that can better represent the characteristics of the real human body in apparent mass and head transmissibility in vertical vibration [34]. Their model described the experimental data better than an earlier model of Matsumoto-Griffin [35][36]. They conclude their studies with an appropriate model to depict the human response with the apparent mass and head transmissibility [34]. In 2006, Liang and Chiang presented a study on biodynamic models of seated human subjects exposed to vertical vibration [38]. They presented a complete study on lumped-parameter models "including pregnant women models" for seated human subjects without backrest support under vertical vibration excitation [38]. Their study concluded with some important points including that the lumped-mass parameter models are limited to one dimensional analysis, and the solution technique suited for linear models is called the Frequency Domain (FD) method. After their study in 2006, Liang and Chiang presented a study where they model the seated human body exposed to vertical vibrations in various automotive postures [39]. The model proposed in their study was analyzed and validated in terms of STH transmissibility and AP mass by various experimental data obtained from published literature.

Despite motor crashes being the leading cause of traumatic fetal morbidity, only a few researchers have tried to study the effects of car crashes on pregnant women. Delote et al. presented a study at 2006, where they aimed to develop a numerical model of the whole body with a gravid uterus, in order to investigate car crash scenarios and to evaluate alternative security systems to improve protection of both the woman and the fetus [74].

Liang and Chiang again studied the biodynamic responses of the seated body [75]. In 2007, Liang, Chiang, and Nguyen studied the biodynamic responses of seated pregnant subjects exposed to vertical vibrations in driving conditions. They modified a 6-DOF model from a non-linear model that is presented earlier by Nash and Muksian [78].

In 2008, Matsumoto and Griffin modeled the resonances of the standing body exposed to vertical whole-body vibration with the effect of posture [40]. In 2009, Serpil and Lopik worked on the same topic as Delotte et al. where they presented a computational pregnant occupant model, ‘Expecting’, for crash simulations. They presented a finite element model ‘Expecting’ which simulates the pregnant woman in car crash scenarios [76]. In 2010, Desta et al. analyzed a 4-DOF model [41]. The 4-DOF was developed originally by Wans and Schimmels [47]. The results of this study showed that the peak value decreases as the vibration magnitude decreases; it also concludes that vibration level difference has a significant effect at resonance frequency and has less effect as frequency increases [41]. Wael Abbas et al. optimize biodynamic seated human models using genetic algorithms [41]. In this study, three biodynamic models are analyzed and optimized. The 4-DOF model of Wan’s and Schimmel gives the best estimation on STH transmissibility, DPM impedance, AP mass with goodness of fit values of 91.2%, 82.1%, and 87.1%, respectively, with the highest average of goodness of fit (87%). [41].

Rakheja et al. carried out a review on the reported data on biodynamic responses of the seated and standing human body exposed to whole-body vibration in different directions [43]. The review also included the associated experimental conditions in order to identify datasets that are likely to represent comparable and practical postural and exposure conditions[43]. In 2011, Srdjevic and Cveticanin identified nonlinear biomechanical models by multi criteria analysis [44]. Their study was an extension of the methodology that was proposed by Srdjevic and Cveticanin in 2004 [45]. The aim of this study was to identify an n-DOF nonlinear biomechanical model [44]. Atia and Bhat [37] extended the 3-DOF model proposed by Bhat and Bhat [33] into a 5-DOF model, to predict the biodynamic behavior of the pregnant mother in terms of the natural frequencies, response to ride vibrations and to obtain the cervical loads [37]. Results indicate that the dynamic loads bearing on the cervix can be of serious concern, particularly when the mother has a past history of preterm birth [37].

In 2012, Rahmatalla and Liu modeled the head and the neck in whole body vibration with an active head-neck model [46]. The model they proposed is a rigid-link dynamic system augmented with passive spring–damper tissue-like elements [46]. The model is able to reasonably capture the softening characteristics of the human head–neck response during fore-aft whole-body vibration of different magnitudes [46]. Gohari et al. modified the bus seat suspension for pregnant woman [77]. Based on the 11-DOF pregnant model presented earlier by Qassem, Gohari designs a special bus seat suspension. To minimize bus seat vibration transmissibility, they used an artificial neural network method.

2.3.3. Walking Analysis

It is seen from the reported literature that Liang and Chiang validate the model they proposed by various experimental data [39]. In order to identify the biomechanical parameters of the proposed model of this study, experimental measurements are needed. However, dynamic experiments cannot be carried out on pregnant women directly. Experimental studies on healthy subjects could be extended to develop a model for a pregnant woman by adding the fetus and the uterus biomechanical properties from literature to the model developed using experimental measurements. Following is the literature on the reported studies concerned with experimental work on walking or running human subjects, which could be used to construct a model of the pregnant woman.

In 2000, Liu and Nigg proposed a simple spring-mass-damper model to simulate human running with rigid mass representing bones and wobbling mass representing soft tissues [48]. The simulated impact forces in this study were compared with experimentally measured impact forces [48]. In 2002, Zajac et al. presented a review on the biomechanics and muscle coordination of human walking [49]. This study aimed to emphasize how muscle driven dynamics based stimulations assist in the understanding of individual muscle function in walking, especially the causal relation between muscle force generation and walking kinetics and kinematics [49].

In 2003, Bhat presented a 5-DOF model to study the dynamic response of the human body to walking generated excitation [50]. In this study the walking human body was modeled as a piecewise time invariant system subjected to periodic excitation [50]. Bhat suggested that parameter identification of this model needs experimental data of walking human subject[50]. In 2007, a review was presented by Brughelli and Cronin [51]. They presented a review of the research on the mechanical stiffness in running and jumping [51]. Accelerometers were mainly used for the purpose of vibration measurements. Kavanagh and Menz presented a review of accelerometry as a technique for quantifying movement patterns during walking [52].

Henriksen et al. presented a randomized trial on the influence of pain and gender on impact load during walking [53]. They found that experimental muscle pain did not affect generation or attenuation of impact loading in either gender [53]. In 2009, Racic et al. presented a literature review on experimental identification and analytical modeling of human walking forces [54]. This study gave a good explanation of the basic concepts of human gait analysis, kinetics, modeling of human walking forces, and kinematics of human body motion [54].

In 2010, AlKhoury et al. presented a study to identify the motive forces on the whole body system during walking [54]. In this study, the body of the walking human is modeled as a 7-DOF system. Experimental measurements were used for identifying the parameters of the 7-DOF model [54]. In 2011, Lipfert et al. presented a model-experiment comparison of system dynamics for the human while walking and running [56]. Kim and Park [57] calculated the effective leg stiffness of human subjects walking at four different speeds by simulating a damped compliant walking model that is slightly modified from the existing compliant walking model [57]. Nardello et al. presented a study where mechanical internal work in human locomotion is measured and predicted [60].

In 2012, Coleman et al. presented a comparison of estimates of leg stiffness in human running derived from previously published models to direct kinematic-kinetic measures [61]. In 2013, Chiang and Chang, presented a new concept of the mechanical design of a humanoid robot. The goal of their study was to build a humanoid robot using a new structure which is more suitable for human-like walking with better descriptions of the characteristics of the knee stretch, heel-contact, and toe-off [62].

2.3.4. Conclusions from Literature Review

The literature review covered three major points: preterm studies, biomechanical modeling, and walking analysis. The studies done on preterm birth attempted to investigate the causes of its occurrence. The vast majority of the research on the causes of preterm birth study the problem from a medical point of view. Some of the studies try to relate the occurrence of preterm birth to bacterial vaginosis [21][18], while some studies are done on certain groups of women to relate the effect of short interpregnancy intervals on the occurrence of preterm birth [24]. There are studies that are done on animals, especially rats [21]. One of the studies focuses on the effect of bed rest, and it suggested that there is no proof that bed rest can prevent preterm birth. It can be seen, as mentioned before that the majority of the studies are concerned with the medical point of view. The current research focuses on the biomechanical aspect of the problem.

Most of the studies use the lumped mass-spring-damper system to model the human body. Fortunately, there are some studies that model the pregnant mother [73][74][75][77]. But these studies model the pregnant woman in the seated position only. None of the studies are concerned with the other activities of the pregnant woman. Hence, it is believed that the pregnant woman's body should be modeled in other positions, specifically the standing and walking positions. As it is believed that prolonged standing and walking can induce a great load on the cervix, it is also believed that it is related to preterm birth.

Walking analysis has caught the interest of many studies. Some of the studies use the spring-mass-damper system to simulate the running human [48]. Others try to experimentally identify human walking forces [54]. It is concluded from the literature that accelerometers are proven to be very reliable in carrying out vibration measurements [51].

2.4. Objectives

According to studies, the rate of preterm births is increasing [1][7]. More studies are trying to find new ways to protect women from the risk of preterm birth. Others are trying to understand the causes of preterm birth. The present research is aimed at determining the amount of cervical loads that are induced from daily activities, since cervical loads and cervical fatigue are one of the factors associated with preterm birth

2.4.1. Solution to the Problem

The objectives of this study are aimed at helping to understand the nature of the cervical loads. It is believed that cervical loads have effects that may lead to preterm birth. The static and dynamic loads bearing on the cervix are believed to have an influence on the cervical resistance which may cause the pregnant woman to deliver preterm. Three models are presented in this study in order to help understand the loads bearing on the cervix and to predict the behavior of the pregnant mother under dynamic excitation conditions.

2.4.2. Cervical Load

Excessive cervical load in pregnant women who are at risk of preterm birth is a serious concern. It is believed that quick movements or daily activities can increase the stress levels. The stress comes from the static and dynamic loads bearing on the cervix. Preterm birth is strongly dependent on the load incident on the cervix. Few studies focus on the effect of vibrations on pregnant women and its relation to cervical load. The first study reported is by Bhat and Bhat [33] where a 3-Degree of Freedom (DOF) model was presented to study the effect of ride vibrations on pregnant woman. This 3-DOF model was developed to the 5-DOF model by Atia and Bhat [37]. This present study proposes a 9-DOF model to study the cervical load caused by the effect of vertical vibrations under walking conditions.

Based on the presented literature, the objectives of this current study are to develop appropriate biomechanical models to study the cervical loads under dynamic input conditions and to validate the model parameters using experimental measurements. A model of the pregnant woman will be developed using the experimentally identified parameters and adding the values for fetus and uterus from literature. Detailed sub objectives are as follows:

1. Two earlier studies focused on the cervical load induced from ride vibration [33][37]. These studies presented the 3-DOF and 5-DOF model representing the pregnant woman's body. But the two models describe the biomechanical properties of the woman at term condition.
2. The parameters of these two models will be modified to represent the biomechanical properties of the woman's body, but at preterm condition.
3. The results from the 5-DOF model will be compared to the results from the 3-DOF model in order to verify the accuracy of its results.
4. As mentioned before, most of the pregnant biomechanical models describe the woman in seated position. The current research will develop a new model that

represents the biomechanical properties of the pregnant woman's body in standing and walking positions.

5. The new developed model will be constructed with 9-DOF, where, 7-DOF represents the body of the woman, while the other 2-DOF represent the fetus and the uterus combination.
6. Results from the 9-DOF will be obtained at two different conditions, preterm and term condition. And those results will be compared to the results obtained from the seated 5-DOF model.
7. The cervical loads will be obtained from each model, the seated 5-DOF and the walking 9-DOF. Depending on the comparison between the cervical loads of the two models, the current study will proceed with the case that shows higher cervical loads.
8. For the chosen model above, it is necessary to identify its parameters, in order to get a better idea of the cervical loads.
9. Experimental measurements will be carried out to continue with the parameter identification process. The responses to vertical vibration will be measured on each body segment.
10. For the purpose of identifying the biomechanical parameters of the chosen model, genetic algorithms optimization function is used to minimize the error between the measured data and the computed responses.
11. The results from the experimented model will be compared to the nominal model results.

2.5. Thesis Organization

The thesis is written in 6 chapters. The next chapter presents the biomechanical modeling. It starts with a 3-DOF model reported by Bhat and Bhat [33], followed by a 5-DOF model developed by Atia and Bhat [37]. Then, the model developed in this study is presented, which is the 9-DOF model. Results from each model will be obtained at two different conditions, preterm and term. Results of the seated models are compared to the walking model results. The results from each model are presented with a discussion of the results. The experimental work done for this study is presented in chapter 4, which describes the experimental apparatus used for the measurements, the experimental methods with the steps taken to ensure the accuracy of the measurements, and the data obtained from the experiments with an analysis of the results. Chapter 5 presents the parameter identification process and the optimization techniques. It focuses mainly on the optimization methods where 4 main points are covered: objective or cost function, the design variables of the objective function, the constraints put on the objective function, and the solver used to minimize the objective function. The results from the optimization process are presented and discussed at the end of the chapter. Chapter 6 presents the conclusion of the proposed study along with the future work suggested.

Chapter 3. Biomechanical Modeling

3.1. Introduction

The exposure of human subjects to vertical or horizontal vibration is a concern in the vast majority of studies reported in the literature. Most of the studies model the human body as a Multi-DOF (MDOF) system in order to analyze the vibration transmissibility to different body segments. The human body is modeled in the seated, standing, and walking positions. Pregnant women are also modeled as MDOF systems.

In this chapter, three biomechanical models are presented. These models are the 3-DOF model presented by Bhat and Bhat [33], the 5-DOF model presented by Atia and Bhat [37], and a third model is a 9-DOF developed in this study. The 3 models are used to predict the biodynamical behavior of the pregnant woman in terms of the natural frequencies, response to ride vibrations and to obtain the cervical loads.

As both systems model the pregnant woman in the seated position, the results from the 3-DOF and 5-DOF models are compared in order to understand the nature of cervical loads in seated position and to determine which model describes the behavior of pregnant woman in better detail. In contrast to the first two models, the 9-DOF describes the pregnant woman in standing position. The results from the 9-DOF model are compared with those from the 5-DOF, in order to obtain an idea about the difference between cervical loads in seated and standing positions, and to determine whether cervical loads have a greater effect in seated or standing position. For each of the three models, natural frequencies, amplitude frequency ratio, and cervical loads are obtained and presented.

3.1.1. Mechanical Properties of Fetus and Uterus

Each of the three models has its 2-DOF, representing the fetus and the combination of the uterus, amniotic fluid and placenta.

The uterus is a hollow pyriform muscular organ located in the pelvis between the bladder in the front and the rectum behind. In the pregnant state, at term, the uterus stretches and expands to accommodate the growing fetus, contains close to 1 to 1.2 liters of amniotic fluid and the placenta, with the volume of the uterus being 5 liters [72]. At term, it weighs 900 to 1000 gm. and measures 35 cm in length.

At term, the fetus weighs up to 3000 to 4000 gm. The fetus floats in the amniotic fluid. It is connected to the wall of the uterus by the umbilical cord through the placenta. The placenta establishes a connection between the mother and the fetus through the umbilical cord. At term, the placenta resembles a circular disc with a diameter of 15 to 20 cm and a thickness of about 2.5 cm at its center. It is spongy and weighs about 500 gm.

Amniotic fluid measures about 50 ml at 12 weeks, 400 ml at 20 weeks and reaches its peak of 1 liter at 36 to 38 weeks. It has a specific gravity of 1.01. It protects the fetus from possible extraneous injury, providing a cushioning effect and acting as a shock absorber, while maintaining an even temperature [72].

Bhat and Bhat, [33] and Atia and Bhat [37] formulated the parameters of these 2-DOF to describe the biomechanical properties at term condition. In the present study, the parameters are changed in order to better describe the conditions of preterm. It will present the biomechanical properties at 37 weeks of pregnancy. The results "at term conditions" presented by Bhat and Bhat [33] and Atia and Bhat [37] will be compared with the results obtained for preterm conditions. Based on the information provided previously about the properties of the fetus and the uterus at preterm condition, the mass of the fetus is assumed to be 2.5 Kg, and the mass of the uterus combination is 2.3 Kg.

In developing the biomechanical model, the masses of the fetus and the uterus, as well as amniotic fluid and placenta combination, have been chosen from previous studies [33][37][72]. It is recognized that the direct use of any published soft tissue properties is not possible, since they have been done on samples of specific dimensions, while the stiffness for a specific biomechanical model will depend on the type of model, number of degrees of freedom of the model, the posture of the subject etc.

In order to synthesize the properties of the presented biomechanical models, the stiffness and mass parameters of the individual degree of freedom of the pregnant mother is assumed to make the natural frequency of each individual degree of freedom in the vertical direction $\frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}} = 2$ Hz. While, the damping parameters of the individual degree of freedom of the pregnant mother is assumed to make the damping ratio of each individual degree of freedom $\zeta = 0.7$.

The fetus and the uterus degrees of freedom have been assigned such properties that will maintain the same assumption [33]. Here, the damping of the amniotic fluid, of the broad and round ligaments holding the uterus to the body and the body damping ratios have been assumed to be 0.7, in the absence of more reliable values. From the previous information, the parameters of the 2-DOF representing the fetus and uterus at preterm condition are as shown in Table 1.

Table 1: Mechanical properties of the fetus and the uterus at preterm and term conditions

	m_i in kg	k_i in N/m	c_i in N.s/m
Preterm Condition	m_1 (fetus) = 2.5	k_1 = 394.784	c_1 = 43.98
	m_2 (uterus combination) = 2.3	k_2 = 363.2	c_2 = 40.46
Term Condition	m_1 (fetus) = 3.5	k_1 = 552.8	c_1 = 61.6
	m_2 (uterus combination) = 2.5	k_2 = 395	c_2 = 43.98

For the three biomechanical models, model formulation is explained and then the model parameters and how they are obtained are shown. The equations of motion are presented and the results obtained are presented and discussed.

3.2. 3-DOF Biomechanical Model

The 3-DOF model was constructed to study the dynamic load on the cervix, which is believed to be one of the causes of preterm birth from a biomechanical point of view. This simple biomechanical model was formulated to help estimate the loads on the cervix [33]. In This study the 3-DOF model is used to predict the cervical loads in sitting position at two different conditions, preterm, exactly at 37 weeks of pregnancy, and at term conditions "42nd week". Results under both conditions are obtained and compared in order to get an idea about the relationship of cervical loads at different phases of pregnancy.

3.2.1. Model Formulation

This biomechanical model is developed to represent the fetus, the uterus and the mother's body, as shown in Figure 3. The model is constructed of three masses: the upper mass representing the fetus, the middle mass representing the uterus, and the lower mass representing the mother's body.

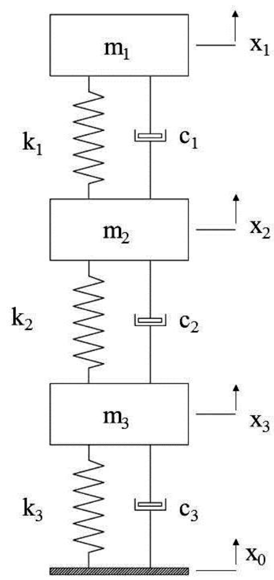

Figure 3: 3-DOF biomechanical model

The fetus is supported by the amniotic fluid and is connected to the uterus through the umbilical cord. The uterus is supported in the body by ligaments which give stiffness and damping properties. The excitation comes in the form of base excitation such as that caused by the road roughness when traveling in vehicles.

3.2.2. Preterm Condition

3.2.2.1. Model Parameters

The values of the masses of the model are chosen from the literature. The mass of the pregnant woman's body is taken as an average value, and the stiffness properties of soft tissues have been chosen from previous studies [63][64][65][66][67][68]. The parameters of the model are presented in Table 2.

Table 2: 3-DOF Model Parameter's Values at preterm condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 2.5$	$k_1 = 394.784$	$c_1 = 43.98$
$m_2 = 2.3$	$k_2 = 363.2$	$c_2 = 40.46$
$m_3 = 65$	$k_3 = 10264.4$	$c_3 = 1143.6$

3.2.2.2. Equations of Motion

As mentioned before, the excitation transmitted to the model comes in the form of base excitation. Assuming the excitation of $x(t) = x_0.\sin \Omega t$, the equations of motion of the system can be written in matrix form as shown in equation (1).

$$[M]\,\{\ddot{x}\} + [C]\,\{\dot{x}\} + [K]\,\{x\} = \{F\,(t)\} \qquad (1)$$

where;

$$[M] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}, [C] = \begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1 + c_2 & -c_2 \\ 0 & -c_2 & c_2 + c_3 \end{bmatrix}, [K] = \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 + k_3 \end{bmatrix},$$

and

$$\{F\} = \begin{Bmatrix} 0 \\ 0 \\ k_3 x_0 \sin \Omega t + c_3 x_0 \Omega \cos \Omega t \end{Bmatrix}.$$

The Eigen values of the system are obtained by solving the homogeneous part of equation (1). The corresponding natural frequencies are given as follows:

ω_1= 6.3687 rad/s, ω_2= 12.7086 rad/s, and ω_3= 19.7999 rad/s.

The FD method is used to obtain the responses in the frequency domain. First, applying Laplace Transform to equation (1) results in:

$$\{H_{3i}(s)\} = [A_3(s)^{-1}]\ \{F_3(s)\} \tag{2}$$

where;

$$\{H_{3i}(s)\} = \begin{Bmatrix} H_{31}(s) \\ H_{32}(s) \\ H_{33}(s) \end{Bmatrix} = \begin{Bmatrix} x_1(s)/x_0(s) \\ x_2(s)/x_0(s) \\ x_3(s)/x_0(s) \end{Bmatrix},$$

$$[A_3(s)] = [(s^2)\ M + (s)\ C + K],$$

and,

$$\{F_3(s)\} = \begin{Bmatrix} 0 \\ 0 \\ sc_3 + k_3 \end{Bmatrix}.$$

Introducing $s = i\omega$ into equation (2), the frequency responses are obtained as:

$$\{H_{3i}(i\omega)\} = [A_3(i\omega)^{-1}]\ \{F_3(i\omega)\} \tag{3}$$

where;

$$\{H_{3i}(i\omega)\} = \begin{Bmatrix} H_{31}(i\omega) \\ H_{32}(i\omega) \\ H_{33}(i\omega) \end{Bmatrix} = \begin{Bmatrix} x_1(i\omega)/x_0(i\omega) \\ x_2(i\omega)/x_0(i\omega) \\ x_3(i\omega)/x_0(i\omega) \end{Bmatrix},$$

$$[A_3(i\omega)] = [(-\omega^2)\ M + (i\omega)\ C + K],$$

and,

$$\{F_3(i\omega)\} = \begin{Bmatrix} 0 \\ 0 \\ (i\omega)c_3 + k_3 \end{Bmatrix}.$$

The magnitudes of the frequency response functions are obtained as:

$$\left| \{H_3(i\omega)\} \right| = \text{abs}\left([A_3(i\omega)^{-1}] \{F_3(i\omega)\} \right) \tag{4}$$

The frequency responses are plotted by evaluating equation (4), and are shown in Figure 4.

3.2.2.3. Results and Discussion

This biomechanical model is developed to give an approximate idea about the loads bearing on the cervix. The static load is due to the weight of the fetus and the amniotic fluid. The static load is estimated as $F_s = 3.5 \times g = 34.335$ N.

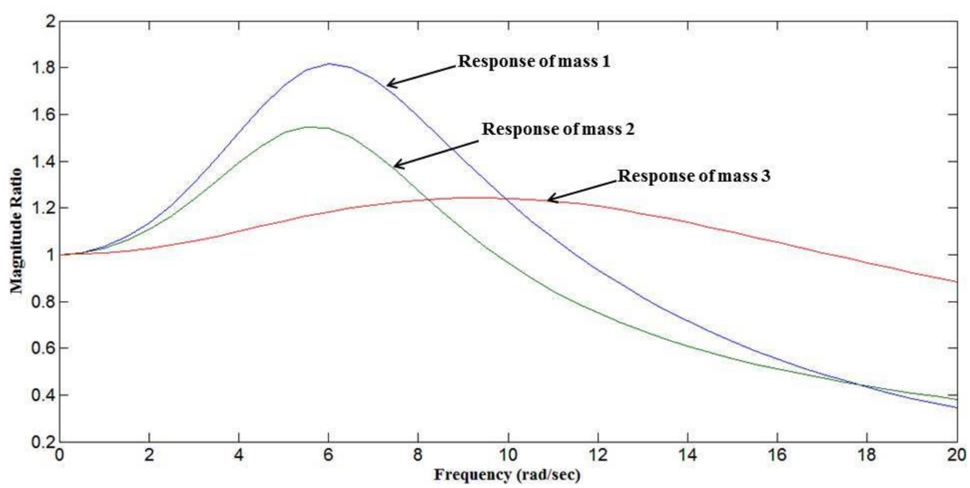

Figure 4: Amplitude Ratio Response of 3-DOF Model at Preterm Condition

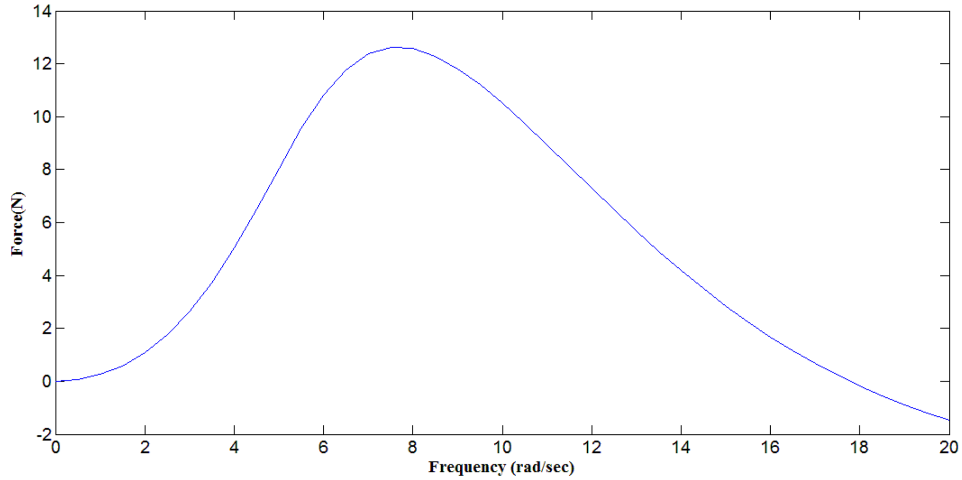

Figure 5: Force on The Cervix of the 3-DOF model at Preterm Condition

The dynamic load on the cervix is estimated by equation (5):

$$F_c = k_1\,(x_1 - x_2) + c_1\,(\dot{x}_1 - \dot{x}_2) \qquad (5)$$

The excitation is assumed to be 10 cm when calculating the amplitude ratio responses. The dynamic load is found to be about 13 N as shown in Figure 5. The total load is calculated as the sum of the static and dynamic load, which is found to be, for the present model, F = 47.335 N. The total load is almost 25% more than the static load.

3.2.3. Term Condition

3.2.3.1. Model Parameters

The values of the parameters at term conditions are suggested by Bhat and Bhat [33].The parameters of the model are presented in Table 3.

Table 3: 3-DOF Model Parameter's Values at term conditions

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 3.5$	$k_1 = 552.8$	$c_1 = 61.6$
$m_2 = 2.5$	$k_2 = 395$	$c_2 = 43.98$
$m_3 = 65$	$k_3 = 10264.4$	$c_3 = 1143.6$

3.2.3.2. Equations of Motion

Equations of motion are the same as mentioned before. The amplitude frequency responses are obtained and the results are shown in Figure 6. The Eigen values of the system are obtained by solving the homogeneous part of equation (1), and the corresponding natural frequencies are given as:

$$\omega_1 = 7.0212 \text{ rad/s}, \omega_2 = 12.7998 \text{ rad/s, and } \omega_3 = 22.0890 \text{ rad/s.}$$

The Amplitude frequency responses are obtained using the FD methods as shown for the preterm condition. The results are shown in Figure 6.

3.2.3.3. Results and Discussion

This biomechanical model is developed to give an approximate idea about the loads bearing on the cervix. The static load is due to the weight of the fetus and the amniotic fluid. The static load is estimated as $F_s = 4.5 \times g = 44.15$ N.

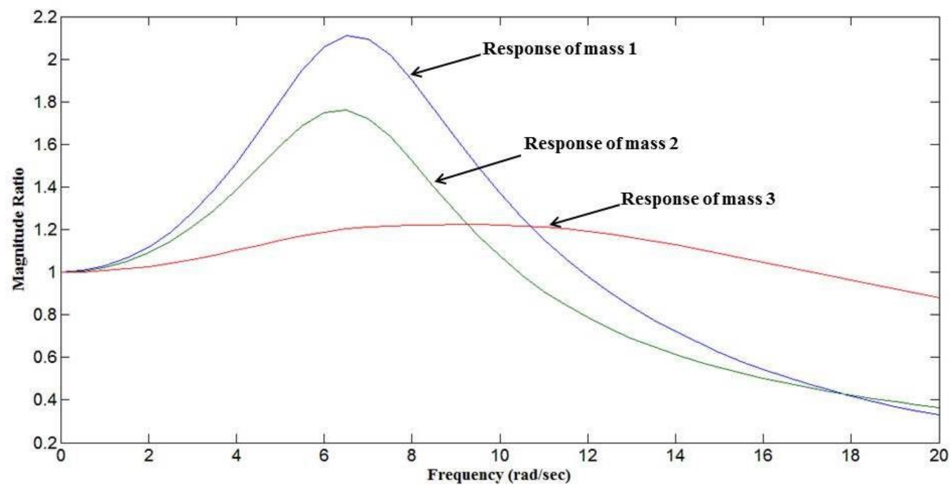

Figure 6: Amplitude Ratio Response of 3-DOF Model at Term Condition

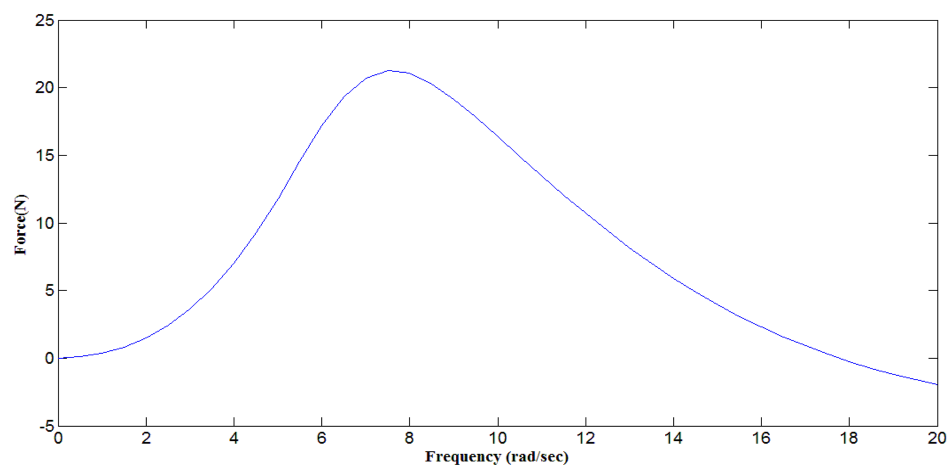

Figure 7: Force on The Cervix of the 3-DOF model at Term Condition

The dynamic load on the cervix is estimated by equation (5):

$$F_c = k_1 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{x}_2) \quad (5)$$

The excitation is assumed to be 10 cm when calculating the amplitude of the ratio responses. The dynamic load is found to be about 21.15 N as shown in Figure 7. The total load is calculated as the sum of the static and dynamic load, which is found to be, for the present case of this model, F = 65.3 N. The total load is almost 30% more than the static load.

3.2.4. Discussion

The 3-DOF that is presented by Bhat and Bhat was used in their study to obtain the loads bearing on the cervix. The parameters they suggested described the biomechanical properties of the pregnant woman at term condition only. It is seen that modifying the values of the parameters to describe more about the preterm condition will give a closer look at the values of cervical loads.

At both conditions, preterm and term, results indicate that the dynamic load bearing on the cervix can be serious, especially if the mother has a history of preterm labor. At preterm conditions, the total load is almost 25% more than the static load, while at term condition; the total load is more than 30% higher than the static load. It is noticed from the results that the responses of masses 1 and 2 "representing the fetus and uterus" change between preterm and term conditions. This change is normal as the values of the parameters representing the fetus and the uterus combination change, while the parameters of the woman's body remain the same for both "preterm and term" conditions.

3.3. 5-DOF Biomechanical Model

The earlier 3 degree of freedom model lumped the mass of the mother into one single mass which is much larger than those of the fetus and the uterus. The disparity in the 3 masses in that model was quite high. Therefore, Atia and Bhat [37] developed the 5-DOF model, as shown in Figure 8, in order to distribute the mother's body into a higher number of degrees of freedom than one. This biomechanical model is formulated to study the behavior of the pregnant woman in terms of the response to ride vibration and to obtain the cervical loads. In this study, the 5-DOF model is used to predict the cervical loads in sitting positions due to ride vibration in vertical direction, at two different conditions, preterm, exactly at 37 weeks of pregnancy, and at term conditions "42 weeks". Results at both conditions are obtained and compared in order to get an idea about the cervical loads at different phases of pregnancy.

3.3.1. Model Formulation

In developing the biomechanical model, the mass of the pregnant mother is reduced by 20 Kg, in order to account for the legs, which are not included in the sitting position. The mass of the mother is distributed over the head, chest, and torso which are represented by m_5, m_4, and m_3, respectively. And the fetus and uterus combination are represented by masses m_1 and m_2.

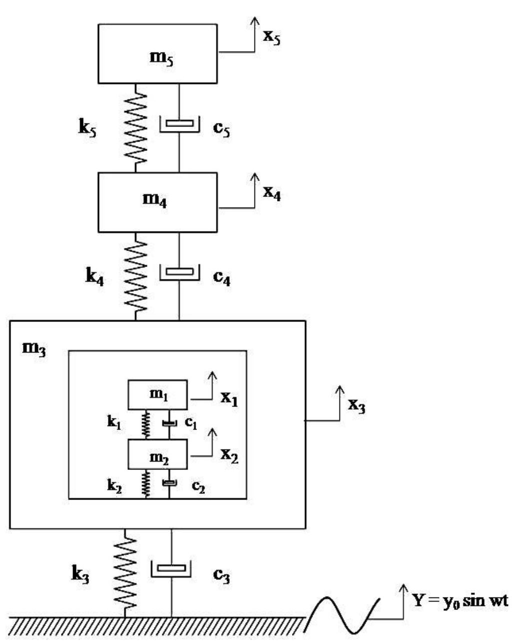

Figure 8: 5-DOF Biomechanical Model

3.3.2. Preterm Condition

3.3.2.1. Model Parameters

As mentioned previously, the values of the parameters representing the fetus and the uterus combination are chosen from the literature. The rest of the parameters are chosen appropriately by Atia and Bhat [37]. The mass of the pregnant woman is taken as an average value. In order to synthesize the properties of this model, the stiffness and mass parameters of the individual degree of freedom of the pregnant mother are assumed to make the natural frequency of each individual degree of freedom in the vertical direction $\frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}}$ = 2 Hz. While, the damping parameters of the individual degree of freedom of the pregnant mother are assumed to make the damping ratio of each individual degree of freedom ζ = 0.7. Consequently, the system parameters assumed in this study are as shown in Table 4.

Table 4: 5-DOF Model Parameter's Values at Preterm Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 2.5$	$k_1 = 394.784$	$c_1 = 43.98$
$m_2 = 2.3$	$k_2 = 363.2$	$c_2 = 40.46$
$m_3 = 25$	$k_3 = 3947.8420$	$c_3 = 439.8230$
$m_4 = 15$	$k_4 = 2368.7000$	$c_4 = 263.8938$
$m_5 = 5$	$k_5 = 789.5684$	$c_5 = 87.9646$

3.3.2.2. Equations of Motion

This model is constructed to study the behavior of pregnant mothers in sitting positions while exposed to ride vibrations. The excitation is assumed to be $y(t) = y_0.\sin \omega t$. The equations of motion of the system could be expressed in matrix form as in equation (6).

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \tag{6}$$

where;

$$[M]=\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 \\ 0 & 0 & 0 & 0 & m_5 \end{bmatrix}, [C]=\begin{bmatrix} c_1 & -c_1 & 0 & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & 0 \\ 0 & -c_2 & c_2+c_3+c_4 & -c_4 & 0 \\ 0 & 0 & -c_4 & c_4+c_5 & -c_5 \\ 0 & 0 & 0 & -c_5 & c_5 \end{bmatrix}$$

$$[K]=\begin{bmatrix} k_1 & -k_1 & 0 & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & 0 \\ 0 & -k_2 & k_2+k_3+k_4 & -k_4 & 0 \\ 0 & 0 & -k_4 & k_4+k_5 & -k_5 \\ 0 & 0 & 0 & -k_5 & k_5 \end{bmatrix}$$

and

$$\{F\}=\begin{Bmatrix} 0 \\ 0 \\ c_3\omega y_0 \cos\omega t + k_3 y_0 \sin\omega t \\ 0 \\ 0 \end{Bmatrix}$$

The Eigen values of the system are obtained by solving the homogenous part of equation (1). The corresponding natural frequencies are:

ω_1 = 6.7823 rad/s, ω_2= 8.1179 rad/s, ω_3= 14.0510 rad/s, ω_4= 19.1908 rad/s, and

ω_5= 21.1071 rad/s

The amplitude frequency responses are obtained by FD method. Applying Laplace Transform to equation (6) will result in:

$$\{H_{5i}(s)\} = [A_5(s)^{-1}]\ \{F_5(s)\} \tag{7}$$

where;

$$\{H_{5i}(s)\} = \begin{Bmatrix} H_{51}(s) \\ H_{52}(s) \\ H_{53}(s) \\ H_{54}(s) \\ H_{55}(s) \end{Bmatrix} = \begin{Bmatrix} x_1(s)/y(s) \\ x_2(s)/y(s) \\ x_3(s)/y(s) \\ x_4(s)/y(s) \\ x_5(s)/y(s) \end{Bmatrix},$$

$$[A_5(s)] = [(s^2)\ M + (s)\ C + K],$$

and,

$$\{F_5(s)\} = \begin{Bmatrix} 0 \\ 0 \\ sc_3 + k_3 \\ 0 \\ 0 \end{Bmatrix}.$$

Introducing $s=i\omega$ into equation (7), the frequency response expressions are obtained as:

$$\{H_{5i}(i\omega)\} = [A_5(i\omega)^{-1}]\ \{F_5(i\omega)\} \tag{8}$$

where;

$$\{H_{5i}(i\omega)\} = \begin{Bmatrix} H_{51}(i\omega) \\ H_{52}(i\omega) \\ H_{53}(i\omega) \\ H_{54}(i\omega) \\ H_{55}(i\omega) \end{Bmatrix} = \begin{Bmatrix} x_1(i\omega)/y(i\omega) \\ x_2(i\omega)/y(i\omega) \\ x_3(i\omega)/y(i\omega) \\ x_4(i\omega)/y(i\omega) \\ x_5(i\omega)/y(i\omega) \end{Bmatrix},$$

$$[A_5(i\omega)] = [(-\omega^2)\ M + (i\omega)\ C + K],$$

and,

$$\{F_5(s)\} = \begin{Bmatrix} 0 \\ 0 \\ (i\omega)c_3 + k_3 \\ 0 \\ 0 \end{Bmatrix}.$$

The magnitudes of the frequency response functions are obtained as:

$$\left| \{H_5(i\omega)\} \right| = \text{abs}\left([A_5(i\omega)^{-1}] \{F_5(i\omega)\} \right) \quad (9)$$

The frequency responses are plotted by evaluating equation (9) and are shown in Figure 9.

3.3.2.3. Results and Discussion

The 5-DOF biomechanical model developed for the pregnant women is approximate. However, the model gives an idea about the static and dynamic loads bearing on the cervix. The static load is due to the weight of the fetus and amniotic fluid, which is approximately $F_s = 3.5 \times g = 34.335$ N.

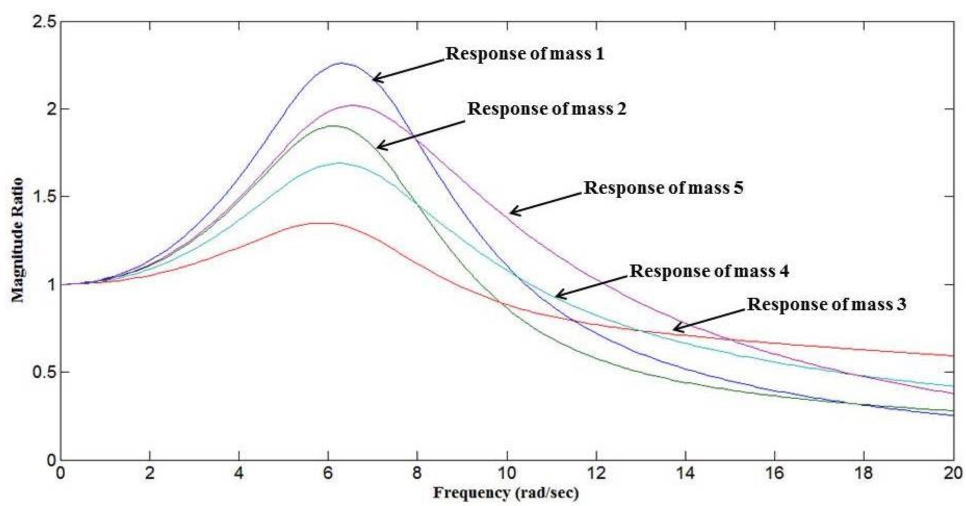

Figure 9: Amplitude Ratio Response of 5-DOF Biomechanical Model at Preterm Condition

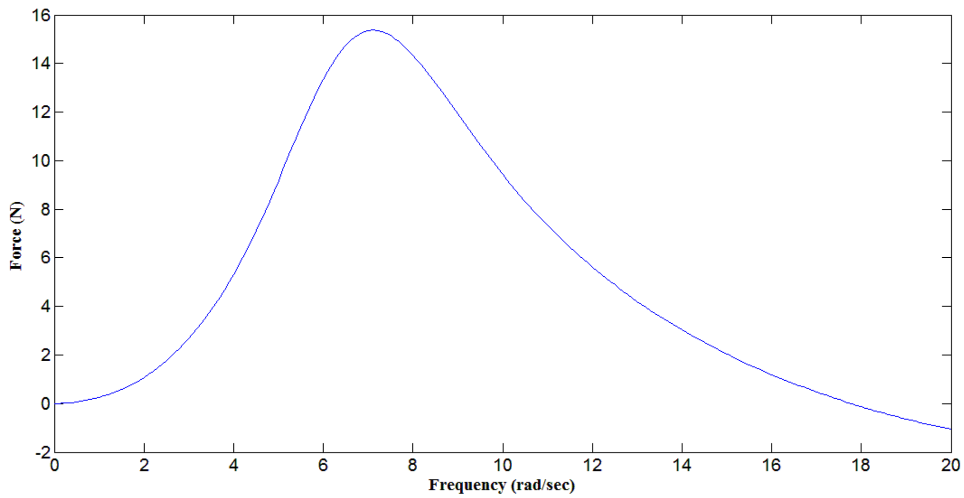

Figure 10: Force on The Cervix of the 5-DOF model at Preterm Condition

The dynamic load on the cervix is given by equation (10) as:

$$F_c = k_1 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{x}_2) \tag{10}$$

An average automobile has a static deflection of about 10 cm and hence a base excitation of 10 cm amplitude is employed to compute the dynamic load on the cervix and is plotted in Figure 10. It can be seen from the figure that the dynamic load on the cervix is about 15.5 N. The total load is calculated as the sum of the static and dynamic load, which is found, for the present case model to be F = 49.835 N. The total load is about 30% more than the static load.

3.3.3. Term Condition

3.3.3.1. Model Parameters

The values of the parameters at term conditions are suggested by Atia and Bhat [37], the parameters are presented in Table 5.

Table 5: 5-DOF Model Parameter's Values at Term Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 3.5$	$k_1 = 552.6978$	$c_1 = 61.5752$
$m_2 = 2.5$	$k_2 = 394.7842$	$c_2 = 43.9823$
$m_3 = 25$	$k_3 = 3947.8420$	$c_3 = 439.8230$
$m_4 = 15$	$k_4 = 2368.7000$	$c_4 = 263.8938$
$m_5 = 5$	$k_5 = 789.5684$	$c_5 = 87.9646$

3.3.3.2. Equations of Motion

Equations of motion are the same as mentioned before. The amplitude frequency responses are obtained and the results are shown in Figure 11. The Eigen values of the system are obtained by solving the homogenous part of equation (6), as:

ω_1= 6.4973 rad/s, ω_2= 7.9563 rad/s, ω_3= 14.0718 rad/s, ω_4= 19.3300 rad/s, and

ω_5= 22.2855 rad/s

The Amplitude frequency responses are obtained using the FD methods as shown for the preterm condition. The results are shown in Figure 11.

3.3.3.3. Results and Discussion

The 5-DOF biomechanical model developed for the pregnant women gives an idea about the static and dynamic loads bearing on the cervix. The static load is due to the weight of the fetus and amniotic fluid, which is approximately $F_s = 4.5 \times g = 44.15$ N.

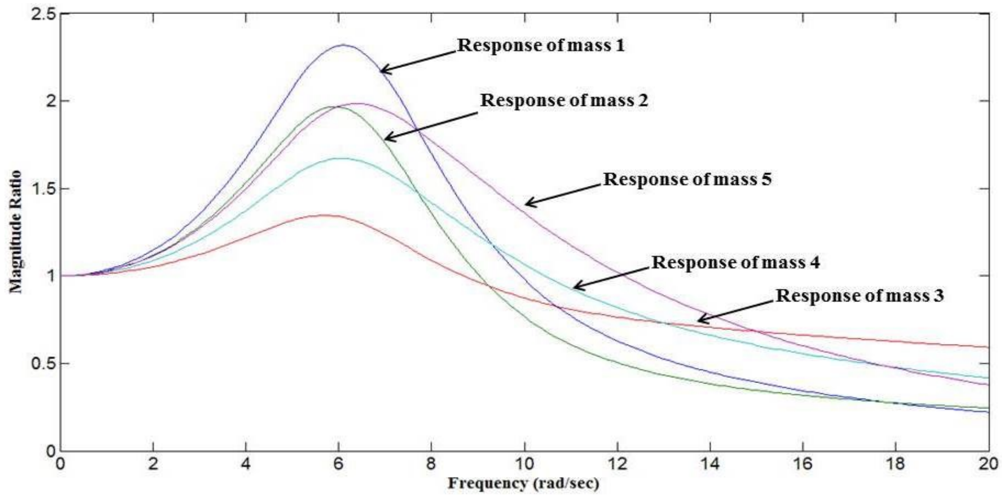

Figure 11: Amplitude Ratio Response of 5-DOF Biomechanical Model at Term Condition

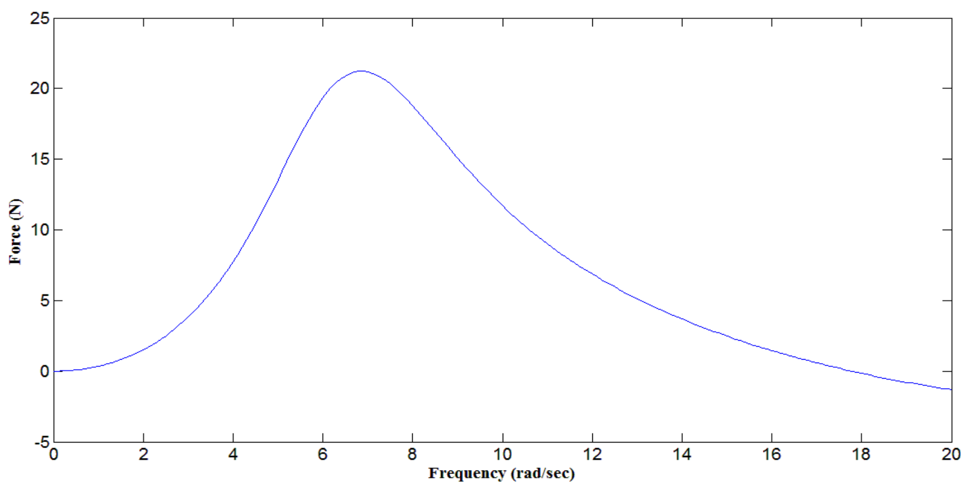

Figure 12: Force on The Cervix of the 5-DOF model at Term Condition

The dynamic load on the cervix is obtained using equation (10):

$$F_c = k_1 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{x}_2) \quad (10)$$

A base excitation of 10 cm amplitude is employed to compute the dynamic load on the cervix and is plotted in Figure 12. It can be seen from the figure that the dynamic load on the cervix is about 21.21 N. The total load is calculated as the sum of the static and dynamic load, which is found to be for the present model, F = 65.36 N. The total load is 35% more than the static load.

3.3.4. Discussion

Atia and Bhat developed the 5-DOF to obtain the loads bearing on the cervix. They modified the 3-DOF model presented earlier by Bhat, in order to get a better estimation of the cervical loads. The parameters they suggested described the biomechanical properties of the pregnant woman at term condition only. It is seen that modifying the values of the parameters to describe more about the preterm condition will give a closer look at the values of cervical loads.

The results from this 5-DOF model agree with those from the 3-DOF model presented in the previous section. It can be seen that at both conditions, preterm and term, results indicate that the dynamic load bearing on the cervix can be serious, especially if the mother has a history of preterm labor. At preterm conditions, the total load is 30% more than the static load, while at term condition; the total load is 35% higher than the static load. It is noticed from the results that the responses of mass 1 “representing the fetus” change between preterm and term conditions. This change is normal as the values of the parameters representing the fetus and the uterus combination change, while the parameters of the woman’s body remain the same for both conditions “preterm and term”. This change is predicted as it agrees with the results from the 3-DOF model.

3.4. 9-DOF Biomechanical Model

In the previous sections, two models are presented, the 3-DOF and 5-DOF models. Results regarding vibration responses and cervical loads are obtained for both models at two different conditions, preterm and term conditions. Results from both models show similar trend and they indicate that cervical load can be serious.

As both of these models describe the pregnant woman in the seated position, the study is extended to a 9 DOF model of the pregnant woman in a standing position in order to understand the cervical load, in the standing/walking positions.

In extending the work done by Atia and Bhat [33][37] in their earlier studies, a 9-DOF biomechanical model is used in order to describe the biomechanical parameters of the pregnant woman in the walking position. This 9-DOF model is used to study the behavior of the pregnant mother in walking position in terms of vibration response and cervical loads. This 9-DOF system describes the movement of the pregnant woman as that of piecewise time variant system for each half-period when one foot is in contact with the ground. This model will help in understanding the effects of response to walking generated excitations on the pregnant mother in terms of vibration response and cervical loads. This model is used to predict the cervical load at two different conditions, preterm condition at 37 weeks, and term condition at 42 weeks.

3.4.1. Model Formulation

This 9-DOF model is used to study the behavior of pregnant walking women in terms of response to walking generated excitations. This model is used to get the response of various body segments to walking generated excitation.

This model represents 9 different body segments as shown in Figure 13. Masses 1 and 2 represent the fetus and uterus combination, respectively. Masses 3, 4, and 5 represent the head, chest, and torso, respectively. Masses 6 and 7 represent the thigh part above the knee. Masses 8 and 9 represent the leg below the knee. The different k_i and c_i represent the stiffness and damping properties.

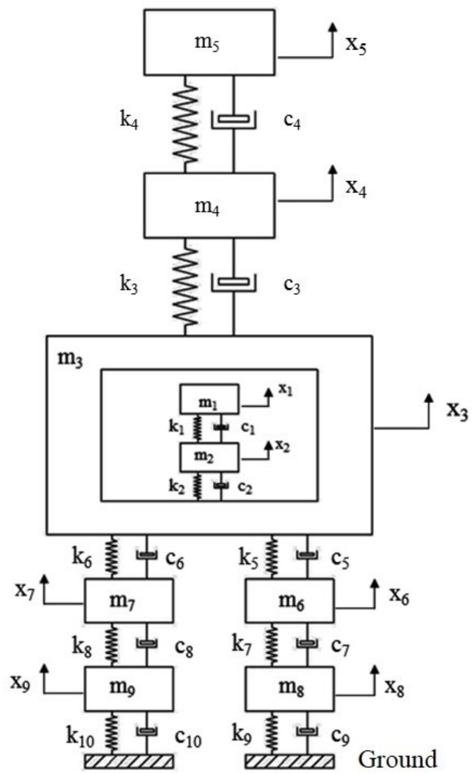

Figure 13: 9-DOF Biomechanical Model

3.4.2. Preterm Condition

3.4.2.1. Model Parameters

The values of the masses of the model are chosen from the literature. The mass of the pregnant woman's body was taken as an average value, while the stiffness values are suggested. The stiffness properties of soft tissues have been chosen from previous studies [33][37][54][63][63][65][65][67][68]. In order to synthesize the properties of this model, the stiffness and mass parameters of the individual degree of freedom of the pregnant mother is assumed to make the natural frequency of each individual degree of freedom in the vertical direction $\frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}} = 2$ Hz. While, the damping parameters of the individual degree of freedom of the pregnant mother is assumed to make the damping ratio of each individual degree of freedom $\zeta = 0.7$. Consequently, the system parameters assumed in this study are as given in Table 6.

Table 6: 9-DOF Model Parameter's Values at Preterm Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 2.5$	$k_1 = 395$	$c_1 = 43.98$
$m_2 = 2.3$	$k_2 = 363.2$	$c_2 = 40.46$
$m_3 = 25$	$k_3 = 183000$	$c_3 = 4750$
$m_4 = 20$	$k_4 = 310000$	$c_4 = 400$
$m_5 = 5.5$	$k_5 = 162800$	$c_5 = 4585$
$m_6 = 9$	$k_6 = 162800$	$c_6 = 4585$
$m_7 = 9$	$k_7 = 162800$	$c_7 = 2064$
$m_8 = 6$	$k_8 = 162800$	$c_8 = 2064$
$m_9 = 6$	$k_9 = 162800$	$c_9 = 2064$
	$k_{10} = 162800$	$c_{10} = 2064$

3.4.2.2. Equations of Motion

This 9-DOF model is used to obtain the responses of various body segments to walking generated excitations. It models the pregnant woman's body as a time variant system subjected to periodic excitation. While walking, only one leg is touching the ground, while the other leg is moving forward without being in contact with the ground. The excitation is assumed to be $y(t) = y_0 \sin \omega t$. The equations of motion are written as shown in equation (11).

While walking, only one leg touches the ground while the other leg is in forward motion towards landing on the ground, which causes the equation of motion to be written for two phases:

- The first phase is when only the left leg is touching the ground,
- The second phase is when only the right leg is touching the ground.

The equations of motion are:

$$[\mathrm{M}]\{\ddot{x}\} + [\mathrm{C}]\{\dot{x}\} + [\mathrm{K}]\{x\} = \{F\} - \{\mathrm{m}\}\mathrm{g} \tag{11}$$

where,

$$[\mathrm{M}]=\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & m_7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_9 \end{bmatrix} \text{ and } \{\mathrm{m}\} = \begin{Bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \\ m_7 \\ m_8 \\ m_9 \end{Bmatrix}.$$

As mentioned before, the equations of motion change depending on which leg is touching the ground. The terms C, K, and F are defined twice as they vary in each phase.

In phase one "only left leg touching" the terms C, K and F are to be defined as follows:

$$[\mathrm{C}] = \begin{bmatrix} c_1 & -c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -c_2 & c_2+c_3+c_5+c_6 & -c_3 & 0 & -c_5 & -c_6 & 0 & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & -c_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -c_4 & c_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & -c_5 & 0 & 0 & c_5+c_7 & 0 & -c_7 & 0 \\ 0 & 0 & -c_6 & 0 & 0 & 0 & c_6+c_8 & 0 & -c_8 \\ 0 & 0 & 0 & 0 & 0 & -c_7 & 0 & c_7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -c_8 & 0 & c_8+c_{10} \end{bmatrix},$$

$$
[K] = \begin{bmatrix}
k_1 & -k_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_1 & k_1 + k_2 & -k_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -k_2 & k_2 + k_3 + k_5 + k_6 & -k_3 & 0 & -k_5 & -k_6 & 0 & 0 \\
0 & 0 & -k_3 & k_3 + k_4 & -k_4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -k_4 & k_4 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_5 & 0 & 0 & k_5 + k_7 & 0 & -k_7 & 0 \\
0 & 0 & -k_6 & 0 & 0 & 0 & k_6 + k_8 & 0 & -k_8 \\
0 & 0 & 0 & 0 & 0 & -k_7 & 0 & k_7 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -k_8 & 0 & k_8 + k_{10}
\end{bmatrix},
$$

and,

$$
\{F\} = \begin{Bmatrix}
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dot{y}_l c_{10} + y_l k_{10}
\end{Bmatrix}.
$$

In the next phase, phase two, “only right leg touching”, the terms C, K and F are:

$$
[C] = \begin{bmatrix}
c_1 & -c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-c_1 & c_1 + c_2 & -c_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -c_2 & c_2 + c_3 + c_5 + c_6 & -c_3 & 0 & -c_5 & -c_6 & 0 & 0 \\
0 & 0 & -c_3 & c_3 + c_4 & -c_4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -c_4 & c_4 & 0 & 0 & 0 & 0 \\
0 & 0 & -c_5 & 0 & 0 & c_5 + c_7 & 0 & -c_7 & 0 \\
0 & 0 & -c_6 & 0 & 0 & 0 & c_6 + c_8 & 0 & -c_8 \\
0 & 0 & 0 & 0 & 0 & -c_7 & 0 & c_7 + c_9 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -c_8 & 0 & c_8
\end{bmatrix},
$$

$$
[K] = \begin{bmatrix}
k_1 & -k_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_1 & k_1 + k_2 & -k_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -k_2 & k_2 + k_3 + k_5 + k_6 & -k_3 & 0 & -k_5 & -k_6 & 0 & 0 \\
0 & 0 & -k_3 & k_3 + k_4 & -k_4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -k_4 & k_4 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_5 & 0 & 0 & k_5 + k_7 & 0 & -k_7 & 0 \\
0 & 0 & -k_6 & 0 & 0 & 0 & k_6 + k_8 & 0 & -k_8 \\
0 & 0 & 0 & 0 & 0 & -k_7 & 0 & k_7 + k_9 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -k_8 & 0 & k_8
\end{bmatrix},
$$

and,

$$\{F\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dot{y}_r c_9 + y_r k_9 \\ 0 \end{Bmatrix}.$$

The natural frequencies and the normal modes of the 9-DOF model and its corresponding normal modes are obtained by solving the homogeneous part of equation (11) and the results are shown in Table 7.

Table 7: Natural Frequencies and Normal Modes for the 9-DOF Model at Preterm Condition

Natural Frequencies (Hz)								
1.2097	3.2912	4.3130	14.29	19.94	27.52	37.75	42.09	43.43
Normal Modes								
1	0.5855	-0.107	3.73e-5	4.46e-5	01.95e-5	1.42e-6	4.03e-7	-2.56e-7
0.6340	-1	0.3909	-0.0019	-0.0044	0.0037	-5.04e-4	-1.78e-4	1.2e-4
0.0046	-0.0154	-0.885	0.0917	0.4278	-0.6900	0.1788	0.0787	-0.0567
0.0046	-0.0164	-0.987	-0.5555	-0.3119	0.1647	-1.89e-4	0.0378	0.3215
0.0046	-0.0165	-1	-0.6483	-0.4324	0.3512	-0.1052	-0.1570	-1
0.003	-0.0105	-0.097	0.0949	1	0.9871	0.0143	-0.5778	0.0713
0.0046	-0.0160	-0.950	0.7026	-0.3440	-0.0686	-1	-0.0638	0.0367
0.0015	-0.0053	-0.309	0.0557	0.7037	1	-0.1947	1	-0.0981
0.0046	-0.0163	-0.977	1	-0.8170	0.6663	0.9315	0.0404	-0.0210

In order to get the amplitude responses, it is sufficient to consider only one phase "left leg or right leg touching" since both phases give the same results. Therefore, the results corresponding to the "only left leg touching" phase will be computed.

The amplitude frequency responses are obtained by using the FD method. Applying Laplace Transform to equation (11) will result in:

$$\{H_{9i}(s)\} = [A_9(s)^{-1}]\ \{F_9(s)\} \tag{12}$$

where;

$$\{H_{9i}(s)\} = \begin{Bmatrix} H_{91}(s) \\ H_{92}(s) \\ H_{93}(s) \\ H_{94}(s) \\ H_{95}(s) \\ H_{96}(s) \\ H_{97}(s) \\ H_{98}(s) \\ H_{99}(s) \end{Bmatrix} = \begin{Bmatrix} x_1(s)/y(s) \\ x_2(s)/y(s) \\ x_3(s)/y(s) \\ x_4(s)/y(s) \\ x_5(s)/y(s) \\ x_6(s)/y(s) \\ x_7(s)/y(s) \\ x_8(s)/y(s) \\ x_9(s)/y(s) \end{Bmatrix},$$

$$[A_9(s)] = [(s^2)\ M + (s)\ C + K],$$

and,

$$\{F_9(s)\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ sc_9 + k_9 \\ 0 \end{Bmatrix} - \frac{\{m\}g}{s}\ .$$

Introducing s=iω into equation (12), the frequency response expressions are obtained as:

$$\{H_{9i}(i\omega)\} = [A_9(i\omega)^{-1}]\ \{F_9(i\omega)\} \tag{13}$$

where;

$$\{H_{9i}(i\omega)\} = \begin{Bmatrix} H_{91}(i\omega) \\ H_{92}(i\omega) \\ H_{93}(i\omega) \\ H_{94}(i\omega) \\ H_{95}(i\omega) \\ H_{96}(i\omega) \\ H_{97}(i\omega) \\ H_{98}(i\omega) \\ H_{99}(i\omega) \end{Bmatrix} = \begin{Bmatrix} x_1(i\omega)/y(i\omega) \\ x_2(i\omega)/y(i\omega) \\ x_3(i\omega)/y(i\omega) \\ x_4(i\omega)/y(i\omega) \\ x_5(i\omega)/y(i\omega) \\ x_6(i\omega)/y(i\omega) \\ x_7(i\omega)/y(i\omega) \\ x_8(i\omega)/y(i\omega) \\ x_9(i\omega)/y(i\omega) \end{Bmatrix},$$

$$[A_9(i\omega)] = [(\omega^2)\ M + (i\omega)\ C + K],$$

and,

$$\{F_9(s)\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ (i\omega)c_9 + k_9 \\ 0 \end{Bmatrix} - \frac{\{m\}g}{s}\ .$$

The magnitudes of the frequency response functions are obtained as:

$$\left|\ \{H_5(i\omega)\}\ \right| = \mathrm{abs}\ (\ [A_5(i\omega)^{-1}]\ \{F_5(i\omega)\}\ ) \tag{14}$$

The frequency responses are plotted by evaluating equation (14) and are shown in Figure 14. It can be seen that the first two peaks close to 1.1 Hz correspond to the masses m_1 and m_2 which are the masses of the fetus and the uterus.

3.4.2.3. Results and Discussion

The 9-DOF biomechanical model developed for the pregnant women is more detailed than the previous models and is able to analyze the pregnant woman's biodynamical behavior during walking generated excitations. The model gives an idea about the static and dynamic loads bearing on the cervix during walking. The static load is due to the weight of the fetus and amniotic fluid, which is approximately $F_s = 3.5 \times g = 34.335$ N.

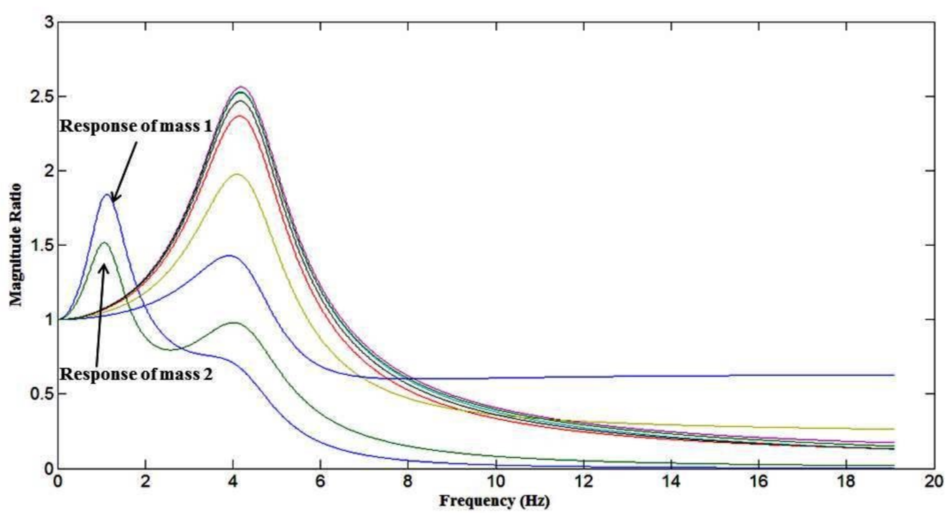

Figure 14: Frequency Response for 9-DOF Model at Preterm Conditions

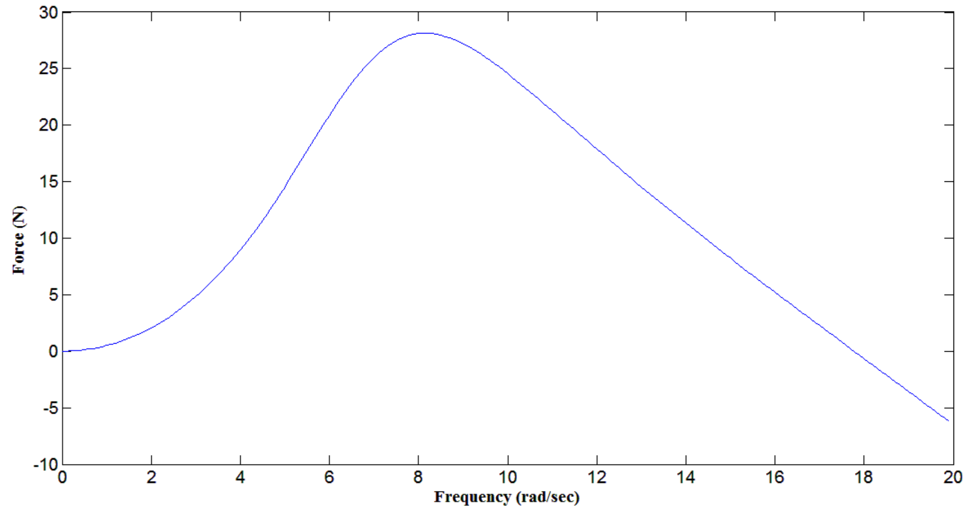

Figure 15: Force on the Cervix of the 9-DOF model at Preterm Condition

The dynamic load on the cervix is given by equation (15) as:

$$F_c = k_1\,(x_1 - x_2)\; + c_1\,(\dot{x}_1 - \dot{x}_2) \tag{15}$$

An average walking excitation has a static deflection of about 20 cm and hence a base excitation of one leg of a 20 cm amplitude is employed to compute the dynamic load on the cervix and is plotted in Figure 15. It can be seen from the figure that the dynamic load on the cervix is about 28.14 N. The total load is calculated as the sum of the static and dynamic loads, which is found for the present case to be F = 62.475 N. The total load is 45% more than the static load.

3.4.3. Term Condition

3.4.3.1. Model Parameters

The values of the parameters of the model at term condition are presented in Table 8.

Table 8: 9-DOF Model Parameter's Values at Term Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 3.5$	$k_1 = 552.6978$	$c_1 = 61.5752$
$m_2 = 2.5$	$k_2 = 394.7842$	$c_2 = 43.9823$
$m_3 = 25$	$k_3 = 183000$	$c_3 = 4750$
$m_4 = 20$	$k_4 = 310000$	$c_4 = 400$
$m_5 = 5.5$	$k_5 = 162800$	$c_5 = 4585$
$m_6 = 9$	$k_6 = 162800$	$c_6 = 4585$
$m_7 = 9$	$k_7 = 162800$	$c_7 = 2064$
$m_8 = 6$	$k_8 = 162800$	$c_8 = 2064$
$m_9 = 6$	$k_9 = 162800$	$c_9 = 2064$
	$k_{10} = 162800$	$c_{10} = 2064$

3.4.3.2. Equations of Motion

Equations of motion are the same as preterm condition. The amplitude frequency responses are obtained and the results are shown in Figure 16. The Eigen values of the system are obtained by solving the homogenous part of equation (11), the corresponding values of the natural frequencies and the normal modes are shown in Table 9.

Table 9: Natural Frequencies and Normal Models for the 9-DOF Model at Term Condition

Natural Frequencies (Hz)								
1.1374	3.498	4.316	14.297	19.948	27.532	37.750	42.091	43.435
Normal Modes								
1	0.4855	-0.1293	3.76e-05	4.48e-05	1.96e-05	1.42e-06	4.04e-07	-2.57e-07
0.6765	-1	0.4729	-0.0018	-0.0044	0.0036	-0.0005	-0.0001	0.0001
0.0052	-0.0203	-0.8855	0.0916	0.4277	-0.6899	0.1788	0.0786	-0.0566
0.0052	-0.0218	-0.9869	-0.5554	-0.3118	0.1647	-0.00018	0.0378	0.3214
0.0052	-0.022	-1	-0.6482	-0.4324	0.3512	-0.1051	-0.157	-1
0.0034	-0.0138	-0.6096	0.0948	1	0.897	0.0143	-0.5778	0.0731
0.0052	-0.0213	-0.9506	0.7025	-0.3439	-0.0685	-1	-0.0638	0.0367
0.0017	-0.0069	-0.309	0.0557	0.7037	1	-0.1947	1	-0.0981
0.0052	-0.0217	-0.9771	1	-0.8169	0.6662	0.9314	0.0404	-0.0213

The Amplitude frequency responses are obtained using the FD methods as shown for the preterm condition.

3.4.3.3. Results and Discussion

The 9-DOF biomechanical model developed for the pregnant women provides information on the static and dynamic loads bearing on the cervix under walking conditions. The static load is due to the weight of the fetus and amniotic fluid, which is approximately $F_s = 4.5 \times g = 44.15$ N.

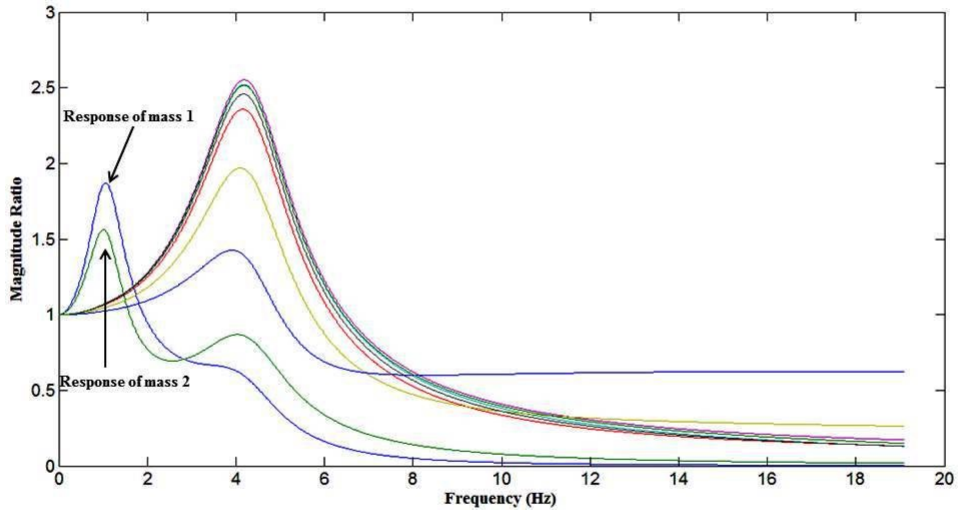

Figure 16: Frequency Response for 9-DOF Model at Term Conditions

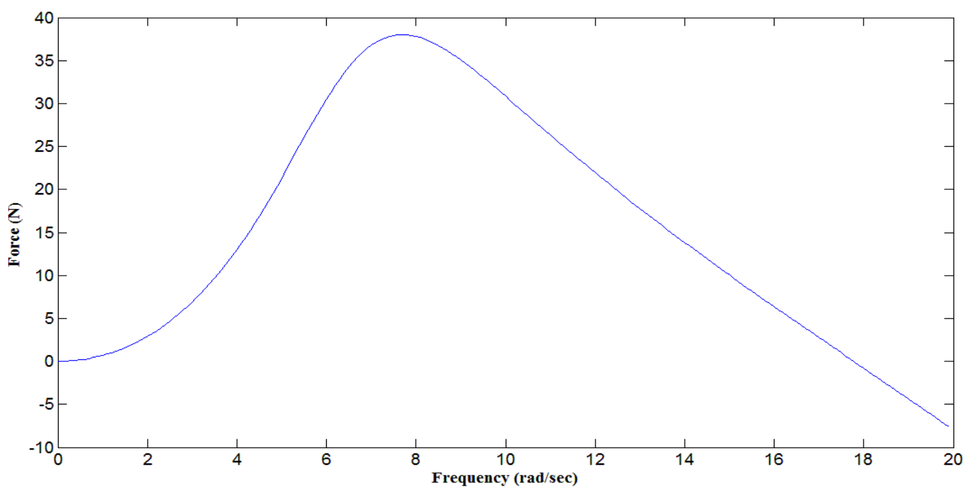

Figure 17: Force on the Cervix of the 9-DOF model at Term Condition

The dynamic load on the cervix is estimated by equation (16) as:

$$F_c = k_1 (x_1 - x_2) + c_1 (\dot{x}_1 - \dot{x}_2) \tag{16}$$

Using an average walking excitation force that causes a static deflection of about 20 cm, a base excitation of one leg of a 20 cm amplitude is employed to compute the dynamic load on the cervix and is plotted in Figure 17. It can be seen from the figure that the dynamic load on the cervix is about 38.03 N. The total load is calculated as the sum of the static and dynamic loads, which is found for the present case of this model to be F = 82.18 N. The total load is 46% more than the static load.

3.4.4. Discussion

Unlike the earlier 3-DOF and 5-DOF model, this 9-DOF model is used to study the loads bearing on the cervix under walking conditions. The model is used to obtain the cervical loads at preterm and term conditions. The results from this model are compared to those from the previous 5-DOF model, in order to determine whether the “seated or walking” position will induce more dynamic load on the cervix of the pregnant woman.

The results from this model show that, in general, the dynamic load in the walking position is higher than the dynamic load in the sitting position. Within the results of the 9-DOF model, it is found that, at preterm condition, the total load is almost 45% higher than the static load, while at term condition, the total load is found to be 46% more than the static load. It is found that the difference between the percentages of the dynamic load and the total load, for the walking case, is not as much as the differences between the percentages in sitting position. It is also noticed that the responses due to the vibration transmitted to the fetus at preterm and term conditions are almost the same. It can be concluded that at both preterm and term conditions, the loads bearing on the cervix are almost the same.

The results shown in Figure 14 are close to the results found in both the 3-DOF and 5-DOF models.

3.5. Summary

In this chapter, 3 biomechanical models are presented. The first two model the pregnant woman in the sitting position, while the third models the pregnant woman in the standing or walking position. The results from the three models are compared in terms of cervical loads.

The results from the 3-DOF and 5-DOF models are compared, in order to verify the results of the 5-DOF model. It is found that the results from the 5-DOF model agree with those from the 3-DOF model. It is noticed that both models show that, in sitting position, the percentage of dynamic load to the total load increases at term condition. The 3-DOF model shows that at preterm condition, the dynamic load is 25% of the total load, while at term condition, it is 30% of the total load. The 5-DOF model yields similar results. It is seen from the results that at preterm condition, the dynamic load is 30% of the total load, while at term condition the dynamic load is 35% of the total load. In general, the seated models give almost similar results in terms of cervical loads.

The 9-DOF model is used to study the behavior of pregnant women during walking in terms of vibration transmissibility and cervical loads. Similar to the seated models, results from the 9-DOF model are obtained at two conditions, preterm and term. It is noted that the percentage of cervical load to the total load is almost the same at both conditions “preterm and term”. At preterm condition, the dynamic load is almost 45% of the total load, while at term condition, the dynamic load is 46% of the total load.

Results from the 9-DOF walking model are compared to those of the seated models and it is found that the loads bearing on the cervix are much higher under walking conditions.

At preterm condition, the 3-DOF and 5-DOF models show that the dynamic loads are 13N and 15N respectively. On the other hand, the 9-DOF model shows 28.8N dynamic load at preterm condition. While at term condition, the 3-DOF and 5-DOF models show the dynamic loads are 21.15N and 21.21N, respectively, the 9-DOF model shows 38.03N dynamic load at term condition. The results obtained show that at both conditions "preterm and term", the cervical loads under walking conditions are almost 50% more than that in seated position. This indicates that the cervical load under walking conditions is of a more serious concern than the seated position. For this reason, this study will focus more on the walking conditions. Therefore, this study will focus more on the 9-DOF walking model rather than the 5-DOF seated model.

Both the 3-DOF and 5-DOF studies were done using the data for the fetus and the uterus from the literature and the mother's body parameters assumed appropriate to the number of degrees of freedom employed. In order to obtain more realistic biodynamic parameters, it is proposed to carry out tests on a healthy person with a 7-DOF model representing the mother's body and adding the parameters for the fetus and the uterus from literature in order to formulate a 9-DOF biodynamic model of the pregnant mother. In preparation to the eventual testing to obtain the biodynamic parameters of a walking subject, preliminary studies were carried out on the 9-DOF. Since it is really hard to identify the parameters of the fetus and the uterus, the same values from literature will be used as in the previous cases. The parameters will be identified through tests for the remaining 7-DOF.

The first step of parameter identification is to obtain vibration responses experimentally for the 7 body segments, which will be presented in the next chapter. In the next chapter, the experiment's design is explained with the experimental apparatus used. The results from the experimental measurements are presented and are used later for parameter identification, by comparing the measured responses to the computed ones. Experiments are carried out on a healthy walking individual. The experiments measure the responses of 7 body segments to walking generated excitation. The 7 body segments considered are: head, chest, torso, 2 masses for right and left thighs and 2 masses for the right and left legs below the knees. The experimental results are later used to identify the biomechanical parameters of the 7-DOF Bio-Mechanical model, employing optimization techniques.

Chapter 4. Measurements of Body Segments Vibration Responses

4.1. Introduction

In the previous chapter, three biomechanical models were presented. The 3-DOF and 5-DOF models described the pregnant woman in the seated position, while the 9-DOF model described the pregnant woman in the walking position. For each of the presented models, amplitude ratio responses and cervical loads were obtained at two different conditions, at preterm and at term.

The two seated models were compared with the walking model in terms of cervical loads. It was found from the results that the loads bearing on the cervix in walking position are almost 50% more than those in seated position. This indicates that in walking position, the cervical loads are more serious, and for this reason, this study focuses more on the biodynamic response of the pregnant woman under walking condition.

The identification of the parameters of the 7 degrees of freedom of the 9-DOF walking model is required, in order to get a better understanding of the loads bearing on the cervix.

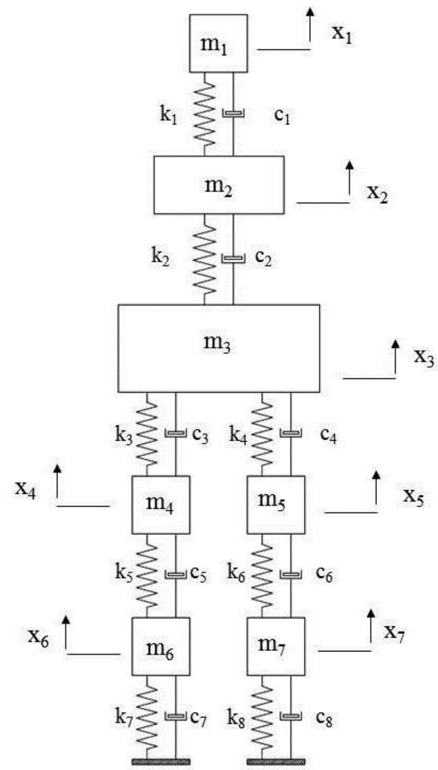

Figure 18: 7-DOF Biomechanical Model

The experimental data is used for the purpose of parameter identification of the 7-DOF model shown in Figure 18. Measured responses to walking generated excitation of the seven body segments are used in identifying the parameters.

The use of accelerometers in order to quantify the movement patterns during walking has increased in recent years, mainly due to the improvement in measurement accuracy and reduction in the size of the accelerometer apparatus [52]. Accelerometers can provide accurate and reliable measurements of segmental accelerations of the body while walking [52]. The benefits of using an accelerometer over more traditional gait analysis instruments include low cost, less restriction of testing environments, and the small size of accelerometers. Moreover, walking with an attached accelerometer is not difficult.

Bhat suggests identifying the biomechanical parameters of his 5-DOF model by obtaining measured responses of different body segments and comparing the measured results to the computed results [50]. Furthermore, to identify the biomechanical parameters for the 7-DOF system of the 9-DOF walking model of the pregnant mother developed in this research, experimental measurements are needed. It is necessary to obtain the responses of 7 body segments, which are described by the 7-DOF model for a healthy subject.

This chapter presents the experimental work that is carried out as the first step of identifying the parameters of the 7-DOF biomechanical system. The responses of the 7 body segments are measured using a tri-axial accelerometer whose specifications are given later. The experimental methods and the different steps of the experiment are explained. At the end of the chapter, the results obtained from the experiments are presented.

4.2. Experimental Apparatus

The accelerometer used is a Gulf Coast Data Concepts [69] product. A USB accelerometer of Model X6-2mini is used to measure the output response of each of the 7 body segments. This accelerometer is used to monitor human motor activity [69].

Figure 19: X6-2mini Accelerometer [69]

The accelerometer is tri-axial one, with a ± 2g or ± 6g range in each axis; it has a 12-bit or 16-bit resolution. It can work on a sample rate of 20, 40, 80, 160 and 320 Hz. The data are saved on the accelerometer in a comma delimited text data file, which facilitates its access. The *X6-2mini* accelerometer collects the data in X, Y and Z directions, Figure 20 shows the sensor orientation.

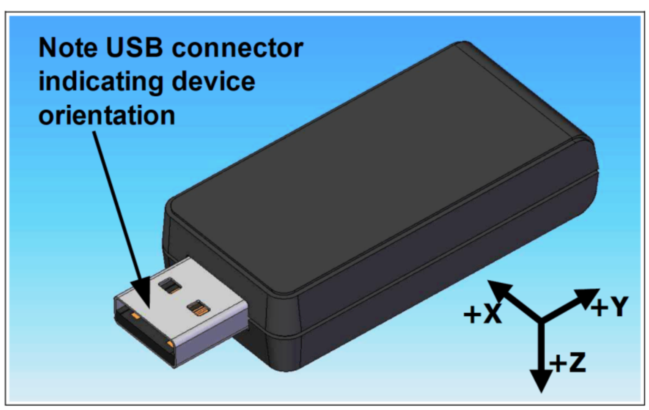

Figure 20: X6-2mini Accelerometer Sensor Orientation [69]

The characteristics for each sensor are shown in Table 10.

Table 10: Accelerometer Sensor Characteristics [69]

Parameter	Condition	Min	Typical	Max	Units
Acceleration Range	High Gain	±1.8	±2.0		g
	Low Gain	±5.6	±6.0		g
12-bit Resolution	High Gain(±2g)		0.001		g/count
	Low Gain(±6g)		0.003		g/count
16-bit Resolution	High Gain(±2g)		0.00006		g/count
	Low Gain(±6g)		0.00020		g/count
Linearity	X,Y axis		±2		%FS
	Z axis		±3		%FS
Zero-g Offset Level Accuracy	High Gain(±2g) X, Y axis	-0.002		0.002	g
	High Gain(±2g) Z axis	-0.004		0.004	g
	Low Gain(±6g) X, Y axis	-0.004		0.004	g
	Low Gain(±6g) Z axis	-0.006		0.006	g

4.3. Experiments

An experiment is designed to obtain the vibration responses of the 7 body segments in the vertical direction during walking. The responses measured are the output of the 7 segments to walking generated excitation. The responses are measured on 7 locations, which are; Head, Chest, Torso, Thighs (Both Legs) and The Leg "Below Knee" (Both Legs).

The experiment is carried out on a healthy walking individual. As the purpose of the experiment is to measure the responses while walking, no specific laboratory environment is required to carry out the experiment. An open space or a hallway with a smooth surface, free of bumps, will be sufficient to carry out the experiment.

The experiment is designed to measure vibrations in the vertical direction. Vibrations are measured at 7 different locations on the body. The accelerometer is mounted on these 7 locations and data is collected along the vertical axis. The accelerometer is mounted using an elastic rope. Since there was only one accelerometer available, the accelerometer is mounted on one body segment at a time.

4.3.1 Experiment Accuracy

The experiment is designed to take only 30 seconds for one trial. The subject is set to walk a distance of 28.8 meters, with 36 footsteps are needed to complete with 0.8 meters for each step. In order to maintain a fixed footstep, a rope of a fixed length is attached to the feet of the subject. This rope is of a length of 0.8 meters. Figure 21 shows the rope fixed to the subject's feet while walking.

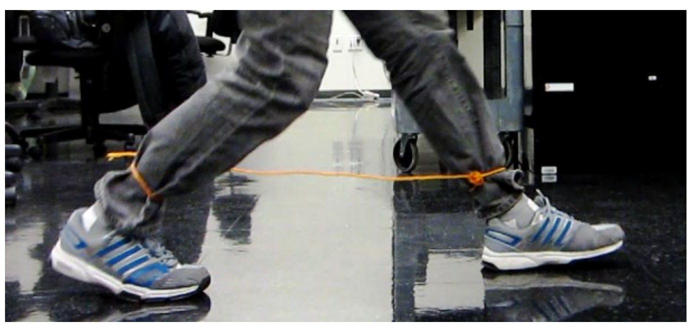

Figure 21: Fixed Length Rope Attached to Subject's Feet

In order to maintain the accuracy of the experiments, the experiment is repeated 3 times for each segment, and then the mean square error of the 3 readings is calculated. The errors between the three trials were not found to be significant. For the segments which represent the thighs and leg "below knee", it is found that there is no difference between the measured data of the right and the left sides. Therefore, the results of only one leg are considered in order to carry out the rest of the intended work.

4.4. Results and Analysis

Vibration responses are measured on 7 segments in addition to the foot excitation measurements. The foot excitation is the input to the system. Data is collected in the vertical direction for all segments. As mentioned before, no difference is found between the responses of the right and left legs. The experiment is carried out for 30 seconds, a specific interval of 10 seconds is chosen out of the 30 seconds.

The results shown next are the data collected in the vertical direction for 6 locations: Head, Chest, Torso, Thigh, Leg (Below Knee) and Foot.

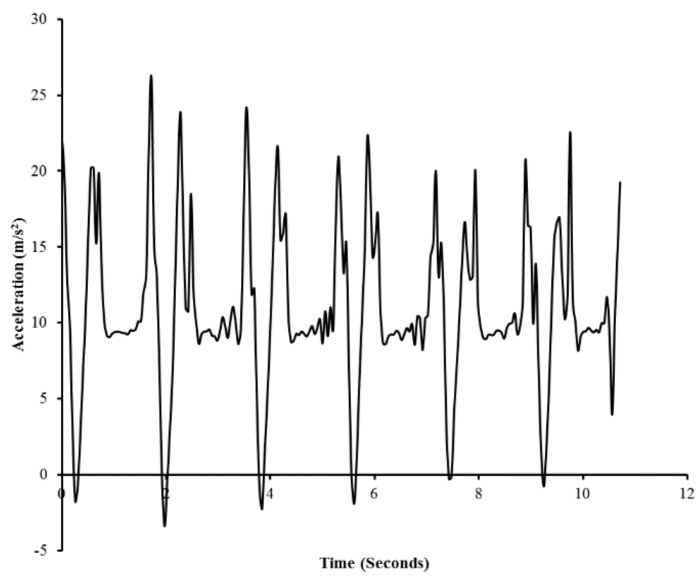

Figure 22: Foot Acceleration

Figure 22 shows the acceleration response of the foot, which is modeled as the input excitation to the system. It shows the acceleration for a time period of 10 seconds. It is found that the foot acceleration response has an average value of 10 m/s^2, which is due to gravity acceleration. It is also noticed that the acceleration comes in a periodic form.

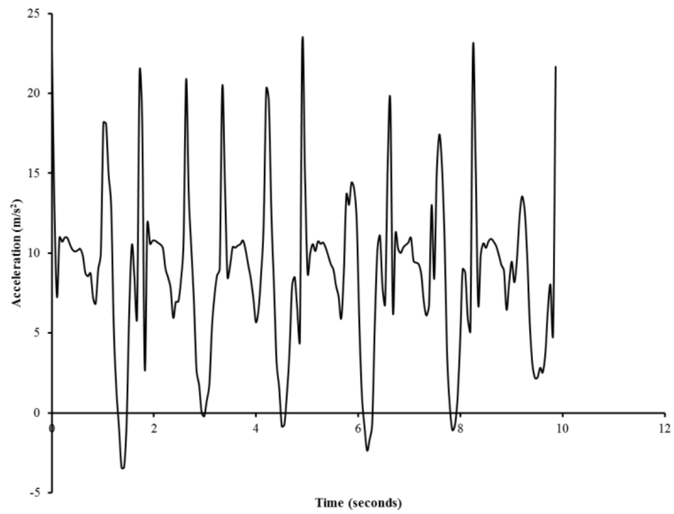

Figure 23: Leg (Below Knee) Acceleration

Figure 23 shows the Leg (Below Knee) acceleration response. This counts for both the right and left legs, which correspond to masses 6 and 7 of the 7-DOF model. It shows acceleration for a time period of 10 seconds. The leg acceleration response varies around 10 m/s^2, which is due to gravity. The output acceleration is periodic.

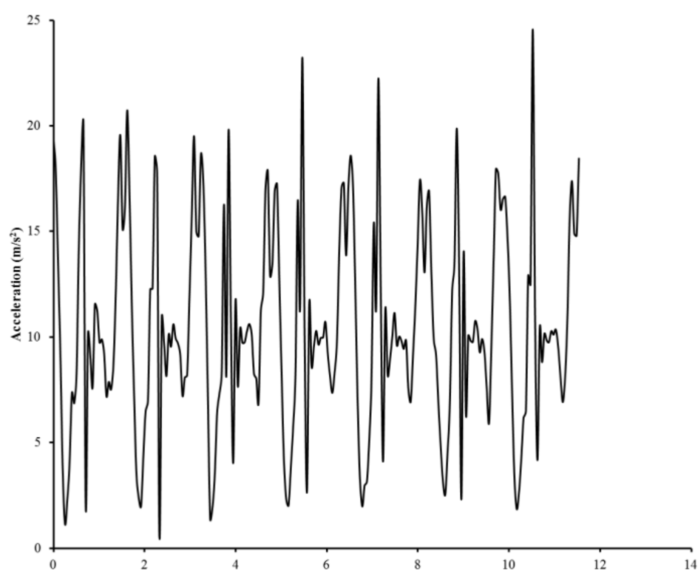

Figure 24: Thigh Acceleration

Figure 24 shows the acceleration response of the thigh. The presented data counts for both legs, which correspond to masses 4 and 5 of the 7-DOF model. Figure 24 shows acceleration for a time period of 10 seconds. The acceleration response of the thigh is also periodic. The acceleration varies around 10 m/s^2, which is close to gravity acceleration due to gravity.

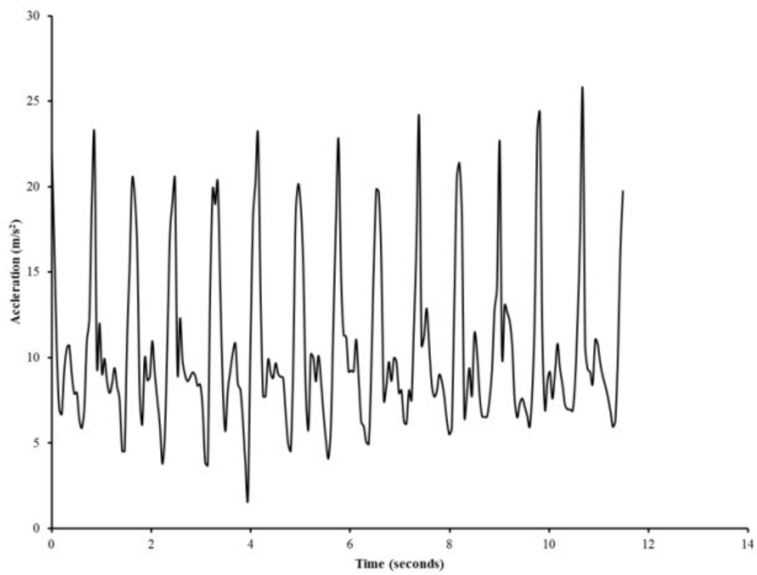

Figure 25: Torso Acceleration

Figure 25 shows the acceleration response of the torso, which corresponds to mass 3 of the 7-DOF model. It shows acceleration for a time period of 10 seconds. The acceleration of the torso comes in a periodic form. It varies around 10 m/s^2, which is close to acceleration due to gravity.

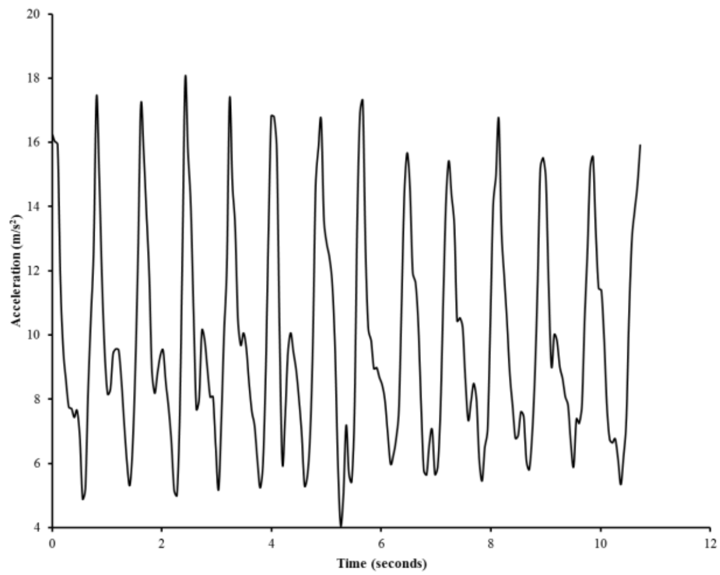

Figure 26: Chest Acceleration

Figure 26 shows the acceleration response of the torso, which corresponds to mass 2 of the 7-DOF model. It shows acceleration for a time period of 10 seconds. It shows that the acceleration response of the chest comes in a periodic form. The acceleration is found to vary around 10 m/s^2, which is close to the gravity acceleration.

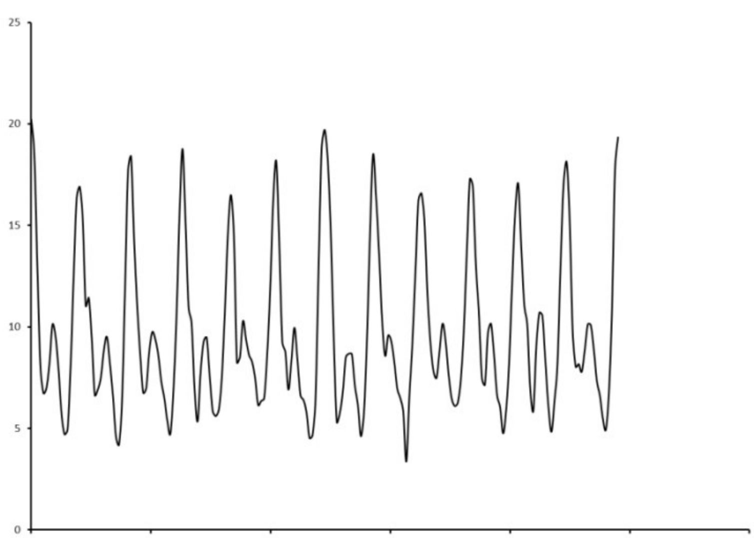

Figure 27: Head Acceleration

Figure 27 shows the acceleration response of the head, which corresponds to mass 1 of the 7-DOF model. It shows acceleration for a time period of 10 seconds. The figure shows that the acceleration response of the head takes the form of an irregular sine wave. The acceleration is found to vary around 10 m/s^2, which is close to gravity acceleration.

4.5. Summary

In this chapter, the experiment designed to measure the responses of the 7 body segments is presented. The apparatus used in this experiment is a tri-axial accelerometer, and it is used in order to measure the acceleration response on each body segment in the vertical direction. The tri-axial accelerometer is a Gulf Coast Data Concept product. The specifications of the accelerometer are presented.

The experimental procedure is described, with the steps taken to ensure the accuracy of the measurements. The experiment is carried out on a healthy walking individual. The subject is required to walk in an open environment, on a smooth surface free of bumps. Data is collected on 7 body segments in the vertical direction. For each of the 7 body segments, the experiment is repeated 3 times, in order to ensure the accuracy of the measured data. The error between each repeated trials is found to be of a very small value, which ensures the precision of the measured data. The results obtained from the experiment are presented. All the responses are in a periodic form, which is expected as the input to the system is periodic.

The next chapter presents the final step of the 7-DOF system parameter identification process. As the computed results are obtained in the frequency domain, the measured responses are transferred to the frequency domain using the *fft* function in Matlab. Then the error function is generated. The error function is the square of the error between the computed and experimental values. Genetic Algorithm optimization function is used to minimize the error function and to obtain the optimum design variables.

Chapter 5. Parameter Identification and Optimization

5.1. Introduction

In chapter 3, three biomechanical models were presented, where two of the three models described the pregnant woman is sitting position, while the third model described the pregnant woman in walking position. The 3 models are compared in terms of responses to vertical vibration and cervical loads. It is found that in walking position, the cervical loads are much higher. Therefore, it was important to identify the biomechanical parameters of the walking model in order to get more detailed information about cervical loads in the walking position.

In chapter 4, the experiment designed to obtain the responses of the 7 segments of the body was presented. In the recent years, accelerometers are used more frequently to measure movement patterns. A tri-axial accelerometer was used to measure the responses of the 7 body segments described by the 7-DOF system.

The computed results of the 7-DOF system of chapter 3 are compared with the measured data presented in chapter 4 in order to identify the parameters of the 7-DOF system of the 9-DOF walking model.

There are many methods which can be used to identify the parameters of the model. Trial and error, and curve-fitting technique are commonly used in order to minimize the error between the computed and measured biodynamic response functions. However, the use of optimization techniques in identifying the biodynamic parameters is more accurate and precise.

Using optimization includes generating an objective function, defining the design variables, defining the constraints imposed on the design process and lastly choosing a suitable solver.

Wael Abbas et al. demonstrated some advantages of using the genetic algorithm optimization function to minimize the error functions [41]. According to Wael Abbas et al. genetic algorithm show better results.

Next in this chapter, the method used to identify the 7 biomechanical parameters is presented, followed by an introduction to the optimization techniques used. Using the optimization method requires generating an objective function, defining the design variables, defining the constraints, and defining the solver used, which are all presented later.

5.2. Parameter Identification Method

The measured acceleration data are first curve fitted in order to obtain functions representing the measured data. These functions are integrated twice to get the corresponding displacement responses.

The responses of the 7-DOF walking model are computed in the frequency domain. In order to compare the computed responses to the measured ones, the measured displacement responses are transferred to the frequency domain using the *fft* (Fast Fourier Transform) function in Matlab.

The displacement responses are transferred to frequency domain, using *fft* function in Matlab. As mentioned before, it is found from the measured data that there is no difference found between the right and left measured responses of the thigh and the leg (below knee).

Therefore, five transfer functions of the measured data are obtained. The Transfer function is the ratio of the output measured response to the input excitation in the frequency domain. The five functions represent the Head, Chest, Torso, Thigh and Leg "Below Knee". After obtaining the transfer functions for the measured vibration responses, the error functions can be generated. The error functions are the square of the difference between the computed and the measured transfer functions. A general or main error function is generated as a combination of the five error functions. This main error function is the objective function to be minimized through the optimization process.

5.3. Optimization Method

Many biomechanical models are constructed using Trial and error, or curve fitting methods so that the error between the computed and the measured responses is minimized [41]. Such curve fitting methods may provide proper fit over a specific range of frequencies. On the other hand, programming based optimization techniques can be effectively used in order to identify the parameters of the biomechanical models involving the use of constrained optimization algorithm [41]. Programming based optimization techniques are widely used in most of the research fields. Optimization techniques are quite general, having a wide range of applicability in diverse fields [70]. Wael Abbas et al. show some advantages to using the genetic algorithm optimization function in order to minimize the error functions [41].

The optimization is the last of the parameter identification steps. A constrained objective function is defined to minimize the error between the computed and measured responses. First, the objective function is generated, which is a function of the targeted design variables. The objective function is the main error function between the computed and measured results. Then, the design variables "DVS" are defined, which are the parameters of the 7-DOF system. This objective function is subjected to a number of constraints, which are defined later. An optimization solver is invoked to minimize the generated objective function. Next, the objective function, DVS, constraints and the selected solver are explained in detail.

5.3.1. Objective Function

The objective function is a combination of the generated error functions. The error functions are the square of the error between the computed and experimental transfer functions. Since two of the transfer functions are identical, only five error functions are generated, representing the five body segments previously mentioned. Equation (17) is the error functions generated, given as:

$$\mathrm{Er_i}(x) = \sum_{f=0}^{20} [E_i(f) - C_i(f)]^2 \text{ , } i = 1, 2, 3\ldots,5 \tag{17}$$

where $E_i(f)$, $C_i(f)$ are the transfer functions obtained from the experiment presented in chapter 4, and the computed responses shown in chapter 3, respectively, corresponding to a discrete frequency f, and x is the DVS vector.

$$\mathrm{Er}(x) = \sum_{i=1}^{5} Er_i(x) \tag{18}$$

The objective function is the sum of the generated error functions. Equation (18) shows the final error function, which is the objective function for the optimization process.

5.3.2. Design Variables "DVS"

The objective function is a function of the design variables vector, which contains 23 DVS, which represent the biomechanical parameters of the 7-DOF system. Table 11 describes the 23 DVS presented. This 7-DOF model is identical to the 9-DOF model of the pregnant woman except for the masses, stiffness, and damping for the fetus and the uterus degrees of freedom.

Table 11: Description of the 23 DVS

Parameter	Representation
m_1, m_2 and m_3	Masses of: Head, Chest and Torso respectively
m_4 and m_5	Masses of the thighs of both right and left leg
m_6 and m_7	Masses of the leg "below knee" of both right and left leg
k_1 and c_1	Stiffness and damping properties between the head and chest
k_2 and c_2	Stiffness and damping properties between the chest and torso
k_3, k_4, c_3 and c_4	Stiffness and damping properties between the torso and thighs for both right and left legs
k_5, k_6, c_5 and c_6	Stiffness and damping properties between the thighs and legs "below knee" for both right and left legs
k_7, k_8, c_7 and c_8	Stiffness and damping properties between the legs "below knee" and the feet for both right and left legs

These 23 variables are the parameters that need to be identified through the optimization process.

5.3.3. Constraints

The DVS are subjected to several equality constraints. These equality constraints are designed to maintain the characteristics of the biomechanical model and to maintain the symmetry of the right and left sides of the body. The equality constraints are demonstrated as following:

- The total mass is kept constant while the individual body segment masses are optimized. Hence, the mass constraints are:

$$m_4 = m_5, m_6 = m_7, \sum_{i=1}^{7} m_i = 75,$$

- It is a reasonable assumption to keep all stiffnesses and coefficients equal. In order to prevent the optimization process driving these parameters to impractical values they are assumed to be equal. Hence the stiffness and damping constraints are:

$$k_3=k_4=k_5=k_6=k_7=k_8,$$

$$c_3=c_4,\ c_5=c_6=c_7=c_8.$$

5.3.4. Optimization Solver

Optimization software based on stochastic search methods, Genetic Algorithm (GA), are used to identify the parameters of the 7-DOF system [70]. Wael Abbas et al. showed some advantages to using the genetic algorithms optimization function to minimize the error functions [41]. The basic idea of the approach of GA is to start with a set of design variables randomly generated, using the allowable values. From the current set of design variables, a subset is selected randomly in order to fit more members of the set. Random processes are used to generate new designs using the selected subset of designs. The size of the set of designs is kept fixed. Since more fit members of the set are used to create new designs, the successive sets of designs have a higher probability of having designs with better fitness values. The process is continued until a stopping criterion is met [70].

A Matlab M-File code is used to invoke the genetic algorithm solver. In order to ensure the accuracy of the results obtained, the optimization calculation is repeated with changing some of the properties of the GA. Results are obtained with different population sizes and different numbers of generations. It is found that results remain the same with different population sizes and different numbers of generations.

5.4. Optimization Results

Genetic algorithm optimization function is used to minimize the main error function. The function is tested with different population sizes and different generation numbers in order to ensure the accuracy of the results, and it is found that with the variation of the population size, the results remain the same. The results came after 19 generations, with an exit flag 1. Table 12 shows the results of the optimized parameters in comparison with the suggested ones.

Table 12: Results Obtained from Genetic Algorithms Optimization

	Values from Biomechanical Model	**Optimization Results**
m_1	5.5	***6.25***
m_2	20	***16.375***
m_3	25	***18.625***
m_4	9	***10***
m_5	9	***10***
m_6	6	***6.875***
m_7	6	***6.875***
k_1	310000	***232500***
k_2	183000	***228750***
k_3	162800	***122100***
k_4	162800	***122100***
k_5	162800	***122100***
k_6	162800	***122100***
k_7	162800	***122100***
k_8	162800	***122100***
c_1	400	***300***
c_2	4750	***3562.5***
c_3	4585	***3438.75***
c_4	4585	***3438.75***
c_5	2064	***1548***
c_6	2064	***1548***
c_7	2064	***1548***
c_8	2064	***1548***

The obtained optimum parameters of the 7-DOF system are augmented with the 2-DOF representing the fetus and the uterus combination in order to form the 9-DOF walking model. This optimized model is used to obtain the responses of the 9 body segments and the cervical loads at two different conditions, preterm and term.

5.4.1. Preterm Condition

5.4.1.1. Model Parameters

The values of the 7-DOF system parameters are obtained from the optimization process, but for the 2-DOF representing the fetus and the uterus combination, the model values are chosen from literature as before. The model data of 9-DOF model is given in Table 13.

Table 13: Optimum 9-DOF Model Parameter's Values at Preterm Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 2.5$	$k_1 = 395$	$c_1 = 43.98$
$m_2 = 2.3$	$k_2 = 363.2$	$c_2 = 40.46$
$m_3 = 18.625$	$k_3 = 228750$	$c_3 = 3562.5$
$m_4 = 16.375$	$k_4 = 232500$	$c_4 = 300$
$m_5 = 6.25$	$k_5 = 122100$	$c_5 = 3438.75$
$m_6 = 10$	$k_6 = 122100$	$c_6 = 3438.75$
$m_7 = 10$	$k_7 = 122100$	$c_7 = 1548$
$m_8 = 6.875$	$k_8 = 122100$	$c_8 = 1548$
$m_9 = 6.875$	$k_9 = 122100$	$c_9 = 1548$
	$k_{10} = 122100$	$c_{10} = 1548$

5.4.1.2. Equations of Motion

Equations of motion are presented in chapter 3. The equations are solved to obtain the natural frequencies and mode shapes. The corresponding values of the natural frequencies and normal modes are shown in Table 14.

Table 14: Natural Frequencies for the Optimum 9-DOF Model at Preterm Condition

Natural Frequencies (Hz)								
1.208	3.28	3.95	13.19	18.077	26.31	31.55	34.51	38.60
Normal Modes								
1	0.588	-0.210	-6.76e-05	2.46e-05	-2.96e-05	-6.48e-06	-2.28e-06	1.89e-06
0.634	-1	0.611	0.0028	-0.0019	0.005	0.0016	0.00067	-0.0007
0.006	-0.027	-0.881	-0.1191	0.1581	-0.8713	-0.3966	-0.1997	0.2598
0.006	-0.029	-0.939	-0.4291	-0.3414	0.2309	-0.0232	-0.0799	-0.5814
0.006	-0.029	-0.955	-0.5264	-0.5228	0.8708	0.4085	0.3027	1
0.004	-0.019	-0.612	-0.1458	1	0.3617	-0.1148	0.6479	-0.1263
0.006	-0.029	-0.965	0.6129	-0.0583	-0.539	1	0.1604	-0.1089
0.002	-0.009	-0.311	-0.0903	0.7851	0.7849	0.5368	-1	0.0962
0.006	-0.030	-1	1	-0.2132	1	-0.8237	-0.0973	0.0471

The Amplitude frequency responses are obtained using the FD method. The results are shown in Figure 28.

5.4.1.3.Results and Discussion

The optimized 9-DOF biomechanical model developed for the pregnant woman provides more realistic information about the static and dynamic loads bearing on the cervix. The static load is due to the weight of the fetus and amniotic fluid, which is approximately $F_s = 3.5 \times g = 34.335$ N.

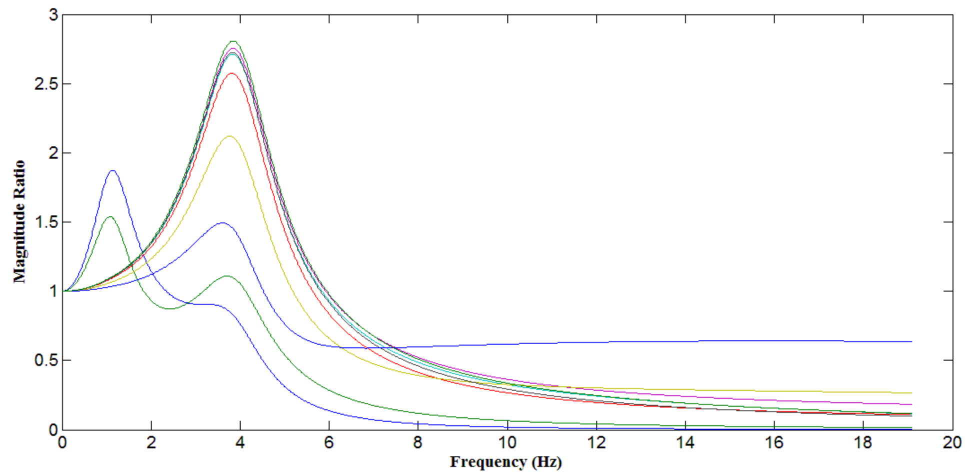

Figure 28: Frequency Response for the Optimized 9-DOF Model at Preterm Conditions

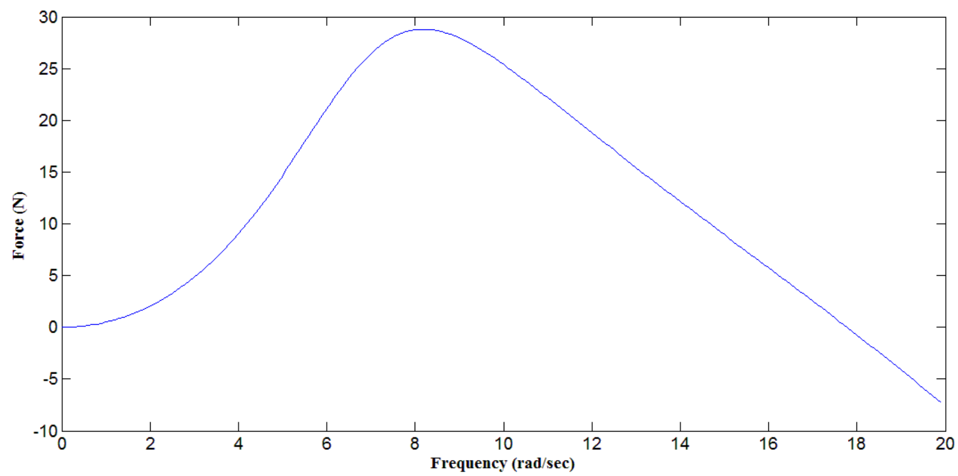

Figure 29: Force on the Cervix of the optimized 9-DOF model at Preterm Condition

Assuming that an average walking excitation has a static deflection of about 20 cm, a base excitation of one leg of a 20 cm amplitude is employed to compute the dynamic load on the cervix which is plotted in Figure 29. It can be seen from the figure that the dynamic load on the cervix is about 28.78 N. The total load is calculated as the sum of the static and dynamic loads, which is found to be, for the present case, F = 63.115 N. The total load is 45% more than the static load.

5.4.2. Term Condition

5.4.2.1. Model Parameters

The values of the 7-DOF system parameters are the parameters obtained from the optimization process, but for the 2-DOF representing the fetus and the uterus combination, values are chosen from literature as before. Table 15 provides the model details for the term condition.

Table 15: Optimum 9-DOF Model Parameter's Values at Term Condition

m_i in kg	k_i in N/m	c_i in N.s/m
$m_1 = 3.5$	$k_1 = 552.6978$	$c_1 = 61.5752$
$m_2 = 2.5$	$k_2 = 394.7842$	$c_2 = 43.9823$
$m_3 = 18.625$	$k_3 = 228750$	$c_3 = 3562.5$
$m_4 = 16.375$	$k_4 = 232500$	$c_4 = 300$
$m_5 = 6.25$	$k_5 = 122100$	$c_5 = 3438.75$
$m_6 = 10$	$k_6 = 122100$	$c_6 = 3438.75$
$m_7 = 10$	$k_7 = 122100$	$c_7 = 1548$
$m_8 = 6.875$	$k_8 = 122100$	$c_8 = 1548$
$m_9 = 6.875$	$k_9 = 122100$	$c_9 = 1548$
	$k_{10} = 122100$	$c_{10} = 1548$

5.4.2.2. Equations of Motion

Equations of motion presented in chapter 3 are used in this analysis. The corresponding values of the natural frequencies are shown in Table 16. The amplitude frequency responses and the normal modes are obtained and the results are shown in Figure 30.

Table 16: Natural Frequencies and Normal Modes for the Optimum 9-DOF Model at Term Condition

Natural Frequencies (Hz)								
1.136	3.4892	3.95	13.195	18.0775	26.3135	31.55	34.514	38.602
Normal Modes								
1	0.4894	-0.2913	-6.82e-05	2.47E-05	-2.97e-05	-6.49e-06	-2.28e-06	1.89e-06
0.6772	-1	0.85	0.0029	-0.0019	0.0051	0.0016	0.0006	-0.0007
0.007	-0.0424	-0.8814	-0.1191	0.1581	-0.8712	-0.3966	-0.1997	0.2598
0.0071	-0.0445	-0.9391	-0.4292	-0.3414	0.2309	-0.0232	-0.0799	-0.5814
0.0071	-0.0451	-0.955	-0.5264	-0.5227	0.8707	0.4085	0.3027	1
0.0047	-0.0292	-0.6118	-0.1458	1	0.3617	-0.1149	0.6479	-0.1263
0.0071	-0.0455	-0.9651	0.6129	-0.0583	-0.5391	1	0.1604	-0.1089
0.0023	-0.0148	-0.3113	-0.0903	0.7851	0.7849	0.5369	-1	0.0962
0.0071	-0.0467	-1	1	-0.2131	1	-0.8237	-0.0973	0.0471

The Amplitude frequency responses are obtained using the FD method. The results are shown in Figure 30.

5.4.2.3.Results and Discussion

The optimized 9-DOF biomechanical model developed for the pregnant woman gives more realistic information for the static and dynamic loads bearing on the cervix. The static load is due to the weight of the fetus and amniotic fluid, which is approximately Fs = 4.5×g = 44.15 N.

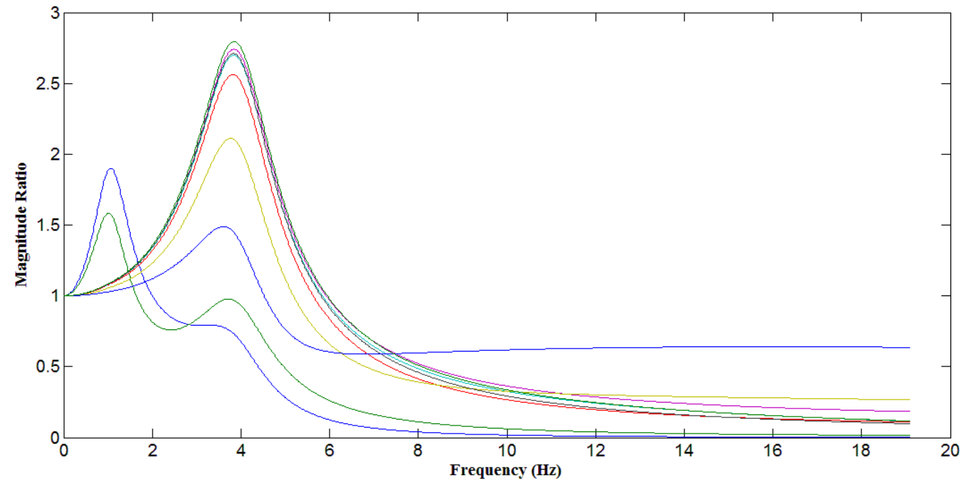

Figure 30: Frequency Response for the Optimized 9-DOF Model at Term Conditions

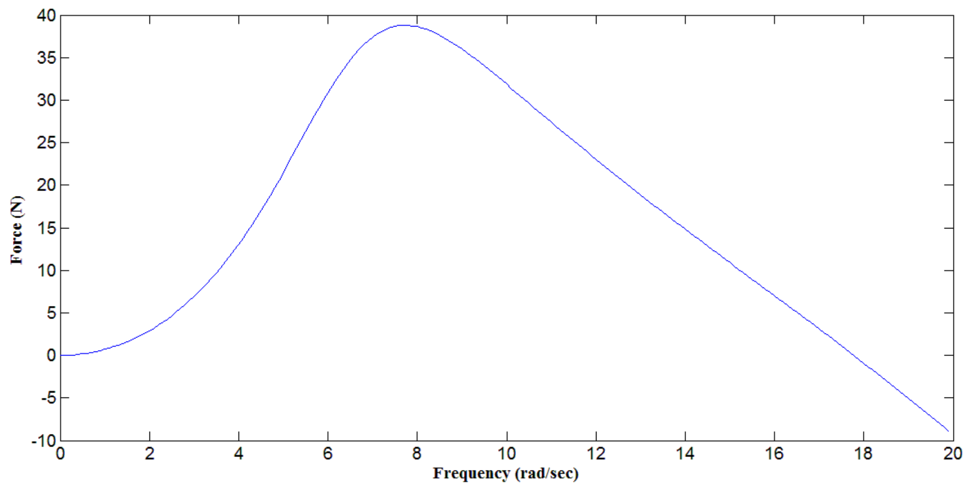

Figure 31: Force on the Cervix of the optimized 9-DOF model at Term Condition

Assuming an average walking excitation has a static deflection of about 20 cm, a base excitation of one leg of a 20 cm amplitude is employed to compute the dynamic load on the cervix which is plotted in Figure 31. It can be seen from the figure that the dynamic load on the cervix is about 38.79 N. The total load, which is the sum of the static and dynamic load, is found to be F = 82.94 N. The total load is 46% more than the static load.

5.4.3. Discussion

The 9-DOF model of this study is developed in order to study the behavior of walking pregnant women in terms of segmental body responses to vertical vibration, and the cervical loads. By obtaining the optimized parameters, the model can give a better idea about the body responses and the cervical loads.

Using the optimized parameters, the results are obtained at two different conditions, preterm and term. The results show that the dynamic load at term condition is higher than preterm condition. However, the percentage of dynamic load of the total load is almost the same at both conditions, where at preterm condition the dynamic load is 45% of the total load, while at term condition the dynamic load is 46% of the total load.

The results obtained from the 9-DOF with the suggested values in chapter 3 are close to the results obtained using the optimized values.

5.5. Summary

The 9-DOF walking model of this study is developed in order to study the behavior of pregnant woman in terms of response to vertical vibrations and cervical loads. It was required to identify the parameters of the walking 9-DOF model. The identification of the parameters is believed to give a better idea about the cervical loads. Experimental measurements are carried out on a walking individual where the responses of the 7 body segments are measured. The responses obtained from the experimental measurements are then curve fitted in order to get an expression for the measured data. The curve fitted functions are integrated twice. Displacement responses are obtained as the results from the integration. The displacement magnitudes are then transferred to the frequency domain using the *fft* function in Matlab.

Next, the transfer functions are obtained. The transfer functions are used to generate the error functions. The error functions are the square of the error between the experimental measurements and the computed results. A final error function is generated as a combination of the five generated error functions. The final error function is set to be the objective function for the optimization process. The objective function consists of the 23 DVS to be identified. These 23 DVS are the biomechanical parameters of the 7-DOF model. GA optimization function is used to minimize the objective function. The genetic algorithm function is tested with different options in order to ensure the accuracy of the results. The results from the optimization process are presented.

Using the parameters obtained from the optimization process, the 9-DOF model is used to obtain results regarding vibration responses and cervical loads. Results from the optimum parameters 9-DOF model are compared to those from the suggested parameters of the 9-DOF model. It is found that the results obtained using the optimized parameters are similar to the results obtained using the suggested values. The results for both types of parameters "suggested and optimized" are obtained at two conditions, "preterm and term". At preterm condition, the suggested values give 28.14 N dynamic load, which is 45% of the total load. While, the optimized parameters give 28.78 N dynamic load at preterm condition, which is 45% of the total load. At term condition, the suggested values give 38.08 N dynamic load, which is 46% of the total load. While, the optimized values give 38.79 N dynamic load, which is 46% of the total load.

It is found that the results obtained using the optimized parameters agree with those obtained using the suggested parameters. This validates the results obtained from the model. The results obtained from the optimized model show that the cervical loads are of serious concern, especially if the woman already has history of preterm birth. It is believed, from the results of this study that extra precautions need to be taken regarding the activities of pregnant women.

Chapter 6. Conclusions and Future Work

6.1. Summary and Conclusions

This study investigates the cervical loads, as it is believed to have an effect on preterm birth. A literature review is done where facts and statistics about preterm birth rates are shown and it showed that preterm birth is of a serious concern. Studies show that the rate of preterm birth is increasing. Studies are concerned with finding a solution to the risk of preterm birth. Some suggest pre-pregnancy awareness. But most of the studies are concerned with the reasons and the causes behind preterm birth. The previous studies are aimed at understanding the causes of preterm birth. Two studies relate preterm birth to cervical loads. The cervical loads are induced from the static load of the fetus and the uterus and dynamic load during movements including quick, sudden movements, daily activities, and from ride vibrations.

The studies that relate preterm birth to cervical loads model the pregnant woman only in the sitting position. Therefore, it is seen that it is necessary to model the pregnant body in positions other than the sitting one, which is the standing position. This study develops a 9-DOF model that represents the pregnant woman's body under walking conditions. The 9-DOF model includes the 2-DOF representing the fetus and uterus combination, and 7-DOF representing the woman's body. Results from the seated and walking models are obtained at two different conditions, preterm and term. The results obtained from the 9-DOF model are compared to the results obtained from the 3-DOF and 5-DOF models, in terms of cervical loads. This comparison is made in order to determine whether the "sitting or walking” conditions produce higher cervical loads. It is found that the cervical loads are higher in the case of walking.

In order to get a better and more detailed understanding of the cervical loads in the walking position, it is necessary to identify the parameters of the 9-DOF walking model. As it is difficult to identify the parameters of the 2-DOF representing the fetus and the uterus combination, it is decided to identify the 7-DOF parameters only. Experimental measurements are needed to identify the parameters of the 7-DOF model. Responses to vertical vibrations on each body segment are measured.

Error functions are generated between the computed and measured results. Then a final error function is generated, which is a combination of the previously generated error functions. The final error function is set to be the objective function of the optimization process. The optimization process included the objective function, the design variables, constraints, and optimization solver. Genetic algorithm optimization solver is used to minimize the final error function. Results are obtained from the optimization process.

The optimum parameters of the 7-DOF model are augmented with the 2-DOF representing the fetus and the uterus combination, so as to form the 9-DOF walking model. The new optimized 9-DOF model is used to obtain the segmental responses of the pregnant woman’s body to walking generated excitations. Results from the optimized 9-DOF are obtained at two conditions, at preterm and at term. Those results are compared to the results from the non-optimized 9-DOF. It is found that the results obtained from the optimized 9-DOF model are very close to the results from the non-optimized 9-DOF model.

The major conclusions drawn from the methods explored and the results obtained in the presented study are as follows:

- The models presented in chapter 3 showed that the loads bearing on the cervix are found to be of a serious concern in both positions, sitting and walking.
- Modeling the pregnant body in the seated and walking positions and obtaining the cervical loads for each position showed that the cervical loads at walking position are higher than those in seated position.
- Identifying the parameters of the 9-DOF walking model gives a better and more detailed understanding of the effects of cervical loads in the walking position.
- The results from the optimized 9-DOF model are very close to the results obtained from the non-optimized 9-DOF model, which shows that the suggested values (non-optimized) of the parameters of the 9-DOF were chosen correctly.

6.2. Future Work

Biomechanical modeling of the human body has attracted the attention of many researchers. Yet, there are some points to which researchers have not given more attention. The effect of vibration transmissibility on pregnant woman needs more research. There is a belief that cervical loads are related to preterm birth. Cervical loads can be induced from various positions: sitting, walking, or other daily activities. Not many biomechanical models are advanced towards pregnant women, and there is no experimental validation for the majority of the models. More modeling is needed in order to understand the loads bearing on the cervix of pregnant women, especially their effect on preterm birth risk, and more experiments are also needed. The present study aims to provide more understating of the vibration transmissibility to the human body from walking excitations, which also helps to understand the dynamic load that comes from movements. However, further work is needed in order to gain a better understanding of the dynamic loads induced on the human body and the vibration transmissibility during walking. Some of the possibilities for further studies are suggested below:

Modeling:

- In this study, three models are presented which model the pregnant woman's body in the seated and walking positions only. The human, or the pregnant woman specifically can be modeled in more positions which describe other daily activities, which can be modeled.
- The three models presented in this research study the vibration transmissibility and the responses of different body segments to vertical vibrations only. The pregnant woman can be modeled in such a way that studies the responses to not only the vertical vibrations, but lateral vibrations as well.

Experiments:

- Experiment Subject: In the present study, the experiment is carried out on one individual subject; it will be beneficial to measure the vibration responses on more than one individual with different physical characteristics (e.g. weight, height, etc….) and different ages.
- Experimental Environment: This experiment is designed to study the human behavior in the walking position. It is also recommended that such experiments could study the behavior of humans during other activities such as standing for long

intervals of time, going up and down the stairs, doing sudden and quick movements, and any other daily activities.

- The effects of vibration transmissibility due to walking or other daily activities can also be related to other problems, such as back pain, neck pain, or problems occurring in certain joints (e.g. knees and hips).

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