Lumbar Spine Dynamic During High Heeled Gait: Musculoskeletal Modeling Contribution

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Abstract. Postural changes, related to increased heel height and its chronic effects, were investigated for many years. However, its relation to low back pain and lumbar vertebra damages may is still controversial. This study aims to determine lumbar kinematic adjustments as high height increase and the contribution of its surrounding muscles to ensure balance and stable motion. In this study, a standard motion capture protocol is used to collect 3D motion data for healthy young females waking with a stiletto shoes with 8.5 cm of heigh. Then a generic full body lumbar model (Rabee 2016) was adjusted to our female subject's anthropometric parameters (weight and height). Joint kinematics, muscle activations, and muscle forces were calculated for each gait cycle using Opensim software package. Preliminary results showed that wearing high-heeled shoes decrease lumbar joint flexion and the increase of axial rotation and lateral bending and induce a higher amount of spine muscle activities to propel legs during locomotion and to maintain spine balance. Consequently, muscular equilibrium changes around intervertebral joints engender higher compressive forces, which may cause discomfort, joint damages, and consequently low back pain. As conclusion, musculoskeletal modeling is a challenging tool to investigate biomechanical effects of altered gaits and predict joint damages in relation to footwear.

Keywords: High heeled gait · Spine muscles · Inter-vertebral kinematics · Low back pain

1 Introduction

High-heeled shoes (HHS) are worn, occasionally and may even regularly, because of femininity attractiveness, fashion reasons and/or socio-professional requirements (Morris et al. 2013). Owing to the widespread use of such footwear among young and elder women, several researchers have focused on their hazardous effects on neuro-musculoskeletal system. Biomechanical investigations had shown that wearing high heel shoes can trigger several dysfunctions on musculoskeletal conditions as consequence of altered foot load distribution and pressure, modified joint functions, excessive energy

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expenditure (Opila-Correia 1991; Cronin 2014; Kerrigan et al. 1998; Stefanyshyn et al. 2000). Because of additional amount of muscular effort required for postural adjustments for balance and stability, HHS can even lead to chronic orthopedic damages such as foot pain and deformities, joint injuries and degenerative diseases (Opila-Correia 1991; Cronin 2014; Kerrigan et al. 1998).

Low back pain and lumbar vertebra damages may be linked to the regularly wearing of footwear with high heels because of posture imbalance and spine muscle alteration (Lee et al. 2001). However, little attention has been paid to this item since the muscular contribution for the trunk balance is more complex during ambulation than standing (Waters et al. 1972; Ono 1969). Understanding of the spinal loads and surrounding muscular actions is challenging issue to evaluate risk factors related to musculoskeletal pains. EMG measurements of paraspinal muscles activities can analyze the balance of the trunk musculature engaged in body movements, but they are not suited to predict force loading on each inter-vertebral joint. Musculoskeletal modeling (MSM) of whole body is a promising approach to highlight the chain reaction of effects that travels up the lower limb and the spine, and to quantify the changes on muscular activations and amount of developed muscular forces to stabilize body posture during an activity (Delp 1990).

The main purpose of this study was to identify muscular contribution for the trunk balance and occurring inter-vertebral joint loading when walking with high-heeled shoes (8.5 cm of height) based on dynamic computational analysis tools. It presents the preliminary results a case study of the effects of heel height on lumbar joint deviations and investigates compensatory mechanisms in order to enhance the biomechanical knowledge of spine damages.

2 Materials and Methods

2.1 Experimental Protocol

In this study, 5 healthy volunteer's women without any neurological or orthopedic troubles were recruited (age: 24.5±4 years, height: 1.62±3.6 m, mass: 55±5.6 kg). After a written consent, participants were asked to perform barefooted and high heeled walking. A Stiletto shoes of 23.7 cm sizing (37 FR – 5.5 US) and 8.5 cm of height is used for this study.

Spherical reflective markers were placed on the whole body in accordance with the full Plug-in gait protocol. 3D marker's trajectories were collected, at 100 Hz, using 34 optoelectronic cameras (Vicon, Oxford Metrics Ltd, Oxford, UK). Ground reaction forces were also collected, at 1500 Hz, with two AMTI force plates (AMTI, Boston, MA, USA).

At least, 10 successful complete gait cycles were collected for each gait conditions. Experiments were conducted in the motion capture platform "Technologies Sport Santé" at the University de Technologies de Compiegne (UTC).

(a) (b)

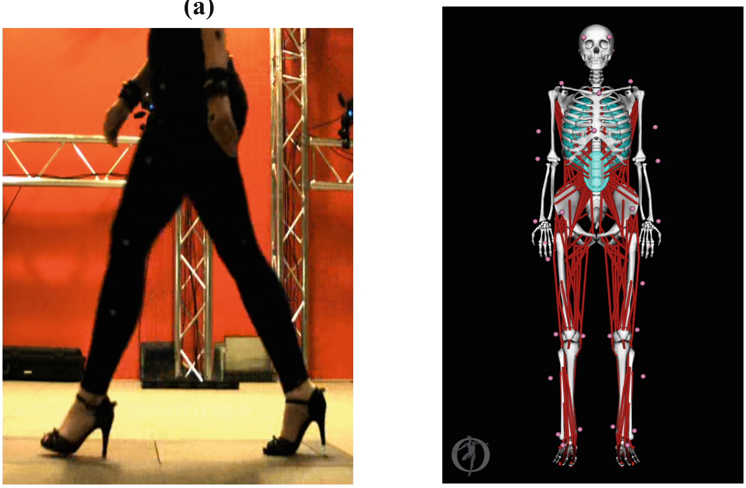

Fig. 1. Experimental protocol (a) vs developed musculoskeletal Model (Rabee 2016) (b)

2.2 Musculoskeletal Model

In this study, a generic full-body lumbar spine musculoskeletal model (MSM) is used [Raabe et al. 2016]. This MMS represent 15 rigid bodies with 38-degree-of-freedom linkage and actuated by 328 muscle-tendon actuators, which include 43 muscles on each lower limb and 242 lumbar muscles to fit the 8 main muscle groups of the lower back: Erector Spinae (ES), Rectus Abdominis (RA), Internal Obliques (IO), External Obliques (EO), Psoas Major (PM), Quadratus Lumborum (QL), Multifidus (MF), and the Latissimus Dorsi (LD). Muscular actuator is modeled as an improved Zajac-type model based on musculotendon parameters from force-velocity-length relationships [Christophy et al. 2012].

As muscle forces are predicted using marker-driven musculoskeletal models to perform tracked experimental motion, OpenSim's virtual markers placement accuracy is crucial. Subsequently, the generic FBLS's virtual markers set was, first, adjusted to suit our experimental protocol and to fit accurate anatomical placements (Fig. 1-b). Second, the generic musculoskeletal model, which describes a male subject with a body height of 1.80 m and a body mass of 75.16 kg, is scaled and adjusted to suit our subject's anthropometric data based on static pose.

Simulation procedure aims to solve the basic dynamic equations in order to predict generalized forces at each joint, muscle activation patterns muscle forces and joint reactions. All estimated data were normalized by the subject's body mass and height.

2.3 Results and Discussions

Compared to barefooted gait, High heels provoke an excessive plantarflexion of the ankle during gait cycle, with a significant reduced range of motion. To balance the center of masse deviation, a decrease knee and hip flexion are observed during the swing phase and consequently an increase of hip adduction-abduction and rotation (Table 1). Lumbar kinematics was also altered. To counter joint restrictions of lower limbs, a slight decrease of the lumbar flexion (2°) is observed accompanied with significant increase of ROM (more than 40%) on lateral bending and axial rotation (Table 1).

Table 1. Lower limbs and lumbar kinematics during barefoot and high heel gaits

	Normal gait_barefoot			High heel gait	
	Mean		Stdv	Mean	Stdv
Ankle flexion-extension	Max	13,21	3,91	−16,22	2,44
	Min	−19,52	6,72	−42,67	4,18
	ROM	32,73	2,81	20,44	3,21
Knee flexion-extension	Max	69,82	4,14	64,79	4,71
	Min	5,05	3,74	7,34	2,98
	ROM	64,77	4,54	57,45	5,52
Hip flexion-extension	Max	48,74	3,10	38,01	4,83
	Min	−14,00	2,81	−14,54	6,50
	ROM	62,74	1,65	52,54	6,80
Hip abduction-adduction	Max	12,07	3,81	15,54	1,95
	Min	−9,09	4,14	−9,53	2,94
	ROM	21,15	6,83	25,07	3,12
Hip rotation	Max	7,66	2,39	2,89	6,84
	Min	−6,90	3,08	−18,59	7,90
	ROM	14,55	2,85	21,48	4,33
Lumbar flexion-extension	Max	7,13	1,23	5,45	6,67
	Min	−3,60	0,62	−7,28	7,45
	ROM	14,73	0,61	12,73	6,69
Lumbar lateral inclination	Max	6,55	6,85	10,31	1,64
	Min	−11,94	0,26	−16,23	3,08
	ROM	18,50	6,59	26,54	2,93
Lumbar Axial Rotation	Max	6,00	14,48	29,54	6,76
	Min	− 31,90	18,60	− 29,68	12,37
	ROM	37,90	4,12	59,22	12,05

Small amplitudes of movement have been observed for the inter-vertebral joints, which decreased from L1 to L5. However, with high heels, inter-vertebral joints were slightly extended with a reduced ROM about 0.5°. Small changes were noticed on transverse and frontal planes (Fig. 2). Lateral bending and axial rotation were increased respectively about 2° on L2-L4 and 1° for L4-L5 (Figs. 3–4).

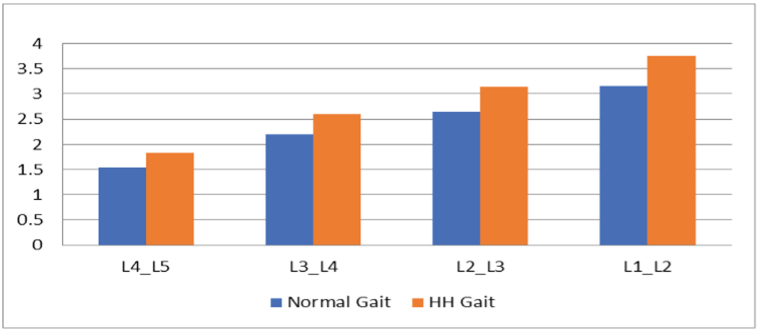

Fig. 2. Intervertebral flexion ROM during barefoot and high heel gaits

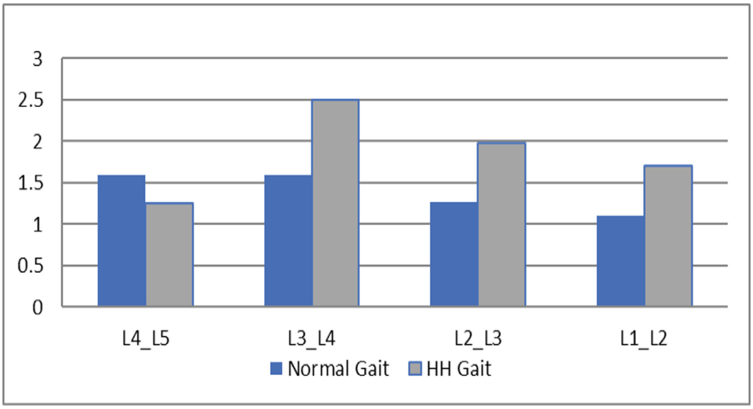

Fig. 3. Intervertebral ROM rotation during barefoot and high heel gaits

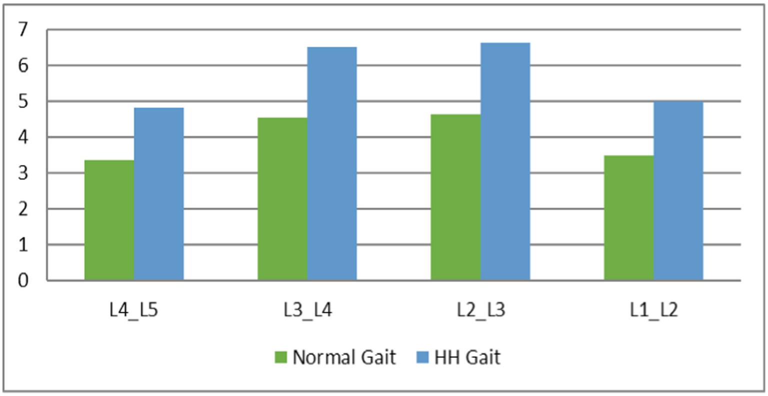

Fig. 4. Intervertebral ROM lateral inclination during barefoot and high heel gaits

As motion is reduced with high heels, net joint moments are reduced in sagittal plane, about 20–30% and an increase amount of at least 10% is observed in frontal and transverse plane as compensatory strategies.

The comparison of lumbar muscular activities between heeled gait conditions and barefoot walking showed larger activation of lumbar muscles because of the gait velocity decrease. An increase of lumbar activation of 40% is observed for ES and RA as they represent primary spine locomotors. However, ES showed an earlier activation than normal to counter the reduction of inter-vertebral flexion and increased axial rotation. With a slight observed activation increase, PM, QL and MF ensure stabilization of the trunk in the lateral plane during an instable gait with high heels (Figs. 5 and 6). For both normal and high heeled gaits, continuous activity of the IO and EO muscles was observed.

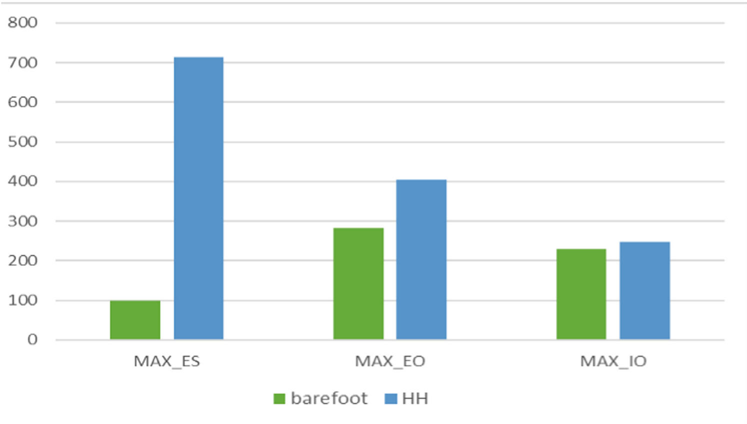

Fig. 5. Maximum muscle forces (N) of erector spinae and oblique muscles with barefoot and high heel gaits

Regarding inter-vertebral joint loading, an increase of compressive forces was observed for all inter-vertebral joints with high heels accompany with a slight shear forces in transverse and frontal axis as consequence of compensatory strategies to maintain stability and balance during motion.

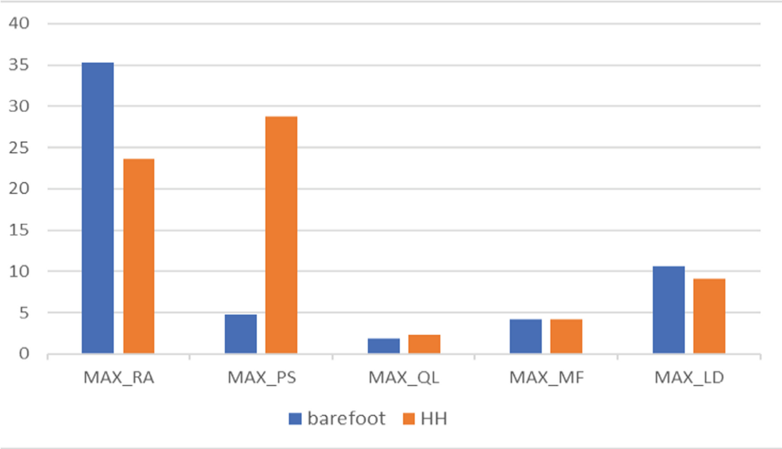

Fig. 6. Maximum muscle forces (N) with barefoot and high heel gaits : Rectus Abdominis, Psoas Major, Quadratus Lumborum, Multifidus and the Latissimus Dorsi

3 Conclusion

Wearing of high heels causes several chronic orthopedic damages because of joint restrictions. Increased plantarflexion of the foot, in addition to small and unstable supporting heel base, may impair foot stability and increase risks of slips and falls as results of unsteady gait (Rezgui et al. 2015). To maintain balance during high heeled motion, postural adjustments are required which induce extra-muscular effort (Srivastava et al. 2012). It has been shown that high heels of 8.5cm cause a significantly decrease of lumbar and inter-vertebral flexion ROM. An increase of lateral bending and axial rotation of spine joints were observed as compensatory phenomena in frontal and transverse planes. Walking with high heels involve a higher amount of muscle forces to propel legs during locomotion and to maintain spine balance. Muscular equilibrium changes around inter-vertebral joints engender higher compressive forces, which may cause discomfort, joint damages and consequently low back pain. The increase of the muscle activation and co-contractions with high heels may lead to increase the metabolic cost of causing earlier muscular fatigue.

As conclusion, even if relation between high heels and low back pain is still a controversial issue, musculoskeletal modeling is a challenging tool to investigate biomechanical effects of altered gaits and predict joint damages in relation to footwear. Estimating lumbar muscular activation patterns and developed forces during gait may enhance the evaluation of risk factors related to musculoskeletal pains when understanding anticipatory postural strategies to maintain balance during instable or pathological motion. It may be helpful for the managing spinal postural dysfunctions and healthcare.

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