COMBINED EFFECTS OF HIGH-HEELED SHOES AND LOAD CARRIAGE ON GAIT AND POSTURE IN YOUNG HEALTHY WOMEN

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Abstracts

The aim of this study was to determine the combined effects of high-heeled shoes and load carriage on gait and posture adaptation. Furthermore, the adaptation of gait and posture to the combined two conditions was examined by a comparison of the measured parameters between experienced and novice groups. 30 participants underwent a quantitative measurement of temporospatial, kinematic, and kinetic parameters of hip, knee, and ankle on both loaded and unloaded limbs using 3D motion analysis. Double support time and stride length increased during high-heeled gait and the magnitude of alteration was greater with a load. Increased plantarflexion was main cause of raised heel. Ankle plantarflexor moment increased with high-heeled but decreased with load carriage. As a result, plantarflexor moment diminished, in addition knee extensor moment exaggerated further. Hip extensor moment increased with heel height but not with load weight, however, hip angle was affected only by the load.

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> “Learning is like rowing upstream; not to advance is to drop back.”

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Note:

This thesis is assembled in article format with three independent articles. These articles are entitled *Combined effects of high-heeled shoes and asymmetrical load carriage on lower extremity kinematics during walking in healthy young women; Effects of asymmetrical load carriage and high-heeled shoes on lower extremity joint kinetics in healthy young women during walking;* and *Combined effects of high-heeled shoes and load carriage on joint kinematics and kinetics of lower extremity during walking in experienced and novice high-heeled shoes wearers*. The first section consists of the general introduction, review of the literature and methodology which encompass all three articles. The three independent articles are then inserted following the first section. Finally there is a conclusion.

Chapter 1: Introduction

1.1 Background to the study

Balance is challenged during gait when the body is forced to make a postural alteration due to disturbances to the body and a failure to compensate posture changes that results in falls. A key to improve the balance is to increase the stability of the system. Often women confront more postural challenges than men due to high-heeled shoes, load carriage on one shoulder or both conditions combined. One can easily notice an altered gait pattern from a woman wearing high-heeled shoes with a heavy purse on a shoulder. She may walk slower than normal individuals, be more careful to walk up and down the stairs, and heavily rely on supports on the bus. These efforts are consciously or unconsciously made to keep the balance to prevent falls. At the same time, neurophysiological and musculoskeletal systems play an important role to keep the balance during walking.

As the desire to look beautiful among women grows in North American society, the number of women wearing high-heeled shoes has increased (Schneider, 2009). Surveys on shoe use have shown that 37% to 69% of women wear high-heeled shoes on a daily basis (Frey, Thompson, Smith, Sanders, & Horstman, 1993). Models wearing high-heeled shoes are easily found in many women's fashion magazines. While many fashion magazines as well as media in North America promote high-heeled shoes for women, the consequences of wearing high-heeled shoes to the gait pattern and postural stability are not well provided elsewhere in the magazine. For example, one of the leading fashion magazines in North America, *Vanityfair* quotes "The thinner the heel the higher the arch, the higher your status and situation" (Blahnik, 2006). From the scientific view, it has been documented that the high-heeled shoes have many negative biomechanical effects on balance, posture, and gait kinematics (Hong, Lee, & Chen, 2007; Lee, Jeong, & Freivalds, 2001; Robbins & Waked, 1997). Hence, there have been numerous studies in biomechanics published comparing different heights of the shoes (Esenyel, Walsh, Walden, & Gitter, 2003; Hsue & Su; 2008; Stefanyshyn, Nigg, Fisher, O'Flynn, & Liu, 2000).

Using bags or purses is a common task in our life. Different types of bags are carried for different purposes. Heavy load carriage for a prolonged period of time could be detrimental to the musculoskeletal system (Al-Khabbaz, Shimada, & Hasegawa, 2008; Holewijn and Lotens, 1992; Knapik, Harman, & Reynolds, 1996). While loads carried and distances traveled vary from report to report, previous studies on load carriage have revealed common patterns of injuries with the majority of them involving either the lower extremities or back. Kinematic and kinetic analyses as well as EMG studies have revealed more in depth information on the biomechanical consequences of load carriage.

Most of the problems and injuries arise from the unstable makings of the shoe with smaller base support that causes a shift in the centre of mass (COM). This is because stability is typically provided through shoe construction (Nigg, Hintzen, & Ferber, 2006). A study from Nigg et al. (2006) suggested that unstably constructed shoes significantly increase instability due to a substantial increase in the movement of COM. The shift of COM occurs not only by wearing high-heeled shoes but also by carrying a load. Often high-heeled shoes are worn with a load on a shoulder creating further postural alterations. Extra load generates greater moment of force and power by the musculoskeletal system and is severer when the load is applied asymmetrically. Legg (1985) suggested that the energy cost is minimized when the load is carried closely attached to the trunk, especially when loads are distributed on both front and back of the trunk. The antero-posterior and lateral stability accomplished by distributed loading is optimized, while loading on one hand or shoulder creates uneven force tilting the body toward the loaded side. An extra load itself affects the gait pattern even with a symmetrical carriage method such as a backpack. According to Martin and Nelson (1986), female subjects displayed a greater sensitivity to the increased load than male subjects in comparison study. An increased load results in a decrease in stride length and increase in stride rate (stride/second). Changes in temporospatial parameters during loaded locomotion are evident from other studies as well (Kinoshita, 1985; Knapik et al., 1996).

Both high-heeled shoes and load carriage are important factors on stability in the dynamic environments such as during simple locomotion or balancing on a moving bus. Although numerous efforts were undertaken into investigating the effects of high-heeled shoes or load carriage alone, the combined effect has not yet been studied. From previous studies it is confident to say that the load carriage puts stress on lower extremities since the lower extremities support the weight of the body, provide the propulsive forces necessary to maintain forward movement of the body and receive the shock of foot contact. The lower extremities, especially the foot, must overcome all stresses for the movement production. A participant with high-heeled shoes has a smaller and unstable supporting base that alters the structure of the lower extremities causing difficulties to accomplish its given roles as a shock absorber or a weight supporter. In order to prevail over the stress on the musculoskeletal system, the body may need to work harder to counter balance all the biomechanical changes. Each joint will display changes in its angle, moments of force, and power, while muscle recruitment patterns will be altered. Therefore, there is a need to understand how both high-heeled shoes and load carriage changes the kinematics and kinetics of the gait as well as the muscle activities in female population.

Consequently, the purpose of this study was to determine the combined effects of high-heeled shoes and load carriage on gait and posture adaptation presented by examining three-dimensional gait kinematics and kinetics of lower extremity joints as well as the temporospatial parameters during walking among healthy 18 to 30 years old females.

Furthermore, the adaptation of gait and posture to the combined two conditions, high-heeled shoes and load carriage, were further examined by a comparison of the measured parameters between experienced and novice high-heeled shoe wearers. It is expected that the results of the study will add understandings to the adaptation of gait and posture to alterations in body.

1.2 Variables

Independent Variables

The independent variables were shoe heights and load weights. Three different shoe heights of 0 cm, 3 cm, and 9 cm were used. The load weights of 0%, 5%, and 10% of the body mass were carried for testing. For the part of comparison between the novice and experienced high-heeled wearer groups, there was an additional variable, a participant type. Two different participant types were used to categorize each participant into either the experienced or novice high-heeled shoes wearer according to their history of wearing high-heeled shoes in the past.

Dependent Variables

a) Temporospatial and kinematic variables

The temporospatial gait parameters were stride length (m), stride width (m), stride time (ms), double and single stance time (ms), and cadence (steps/min) or self-selected walking velocity (m/s). Temporospatial parameters provide information about balance during the gait. It has been suggested that the stride length and stride time are parameters related to gait-patterning mechanism and stride width and double support time are related to balance control mechanism during locomotion (Gabell & Nayak, 1984). Step length and width together indicate the size of base of support and approximate position of the centre of pressure (COP). Examination of step length and step width, in conjunction with the data on COM can therefore provide information about the balance in the absence of force plate data.

In addition, single and double limb support time provide information on periods of relative instability and stability (Said et al., 2008; Winter, 1987).

The kinematic parameters included ankle, knee, and hip joint angle in all three planes as well as range of motion. A mean value at heel strike and toe off and a peak angle for each joint angle were taken to be compared between the conditions and groups.

b) Kinetic variables

Kinetic parameters of the dependent variable included an average value at heel strike and toe off and peak moment of force (N·m) for each joint in lower extremity for both left and right limb. Kinetic variables were normalized by body weight (kg) for the comparison between the subjects, therefore, dependent variables were moment of force (N·m/Kg).

c) Static Balance Measurements

To provide information on the functional stability, baseline balance test (ABC scale) was performed as dependent variable. Along with the questionnaire, static balance test was performed to achieve data on participants' postural stability in all different conditions. Static postural stability was measured by timed stance tests. A single leg stance test and tandem stance test were completed with and without eyes closed at each of combined load and heel-height conditions.

Table 1. Independent and dependent variables of interests

INDEPENDENT VARIABLES	
Category	Description
Shoe Heights	0 cm 3 cm 9 cm
Load Weights	0 % BW 5 % BW 10 % BW
Subject Types	Experienced Novice

DEPENDENT VARIABLES	
Category	Description (unit)
Temporospatial Parameters	Stride Length (cm) Step Length (cm) Stride Time (s) Double Stance Time (s) Single Stance Time (s) Cadence (steps/min)
Kinematic Parameters	Peak joint angle (º) Range of Motion (º)
Kinetic Parameters	Moment of Force (N·m/Kg) at heel strike Moment of Force (N·m/Kg) at toe off Peak Moment of Force (N·m/Kg)
Static Balance Measurements	Single Leg Stance Test (s) Tandem Stance Test (s)

1.3 Hypothesis

First of all, a condition with no heel height and weight carriage was viewed as the most stabled gait and this was a control condition. Stable gait is defined as balanced gait in which a full postural control is assured (Angeli, Church, Henley, Coleman, Lennon, & Miller, 2006). Each participant performed her most optimum and efficient movement in self-selected speed with no obstructions during the control condition. Therefore, it was hypothesized that the gait pattern will be changed as weight of the load (5% and 10% of body weight (BW)), height of the shoes (3 cm and 9 cm), or both were added. It was hypothesized that when maximum weight and heights were introduced to the participants the degree of biomechanical changes to the gait will be at its greatest. More specifically following omnibus hypotheses were tested in the present study.

In comparison with the control condition, which participants wore no high-heeled shoes and load, when weight of the load and height of the shoes were increased

a) stride length will decrease and a stride time will increase;

b) stride width and a double support time will increase;

c) cadence will decrease;

d) lower extremity joint angles will be significantly altered especially in sagittal plane;

e) displacement of COM will be significantly larger;

f) ankle will display significantly increase in plantarflexion from the raised heel, in turn causes knee and hip angle to compensate for the changes in ankle by decrease joint movements;

g) peak moment of lower extremity joints on will be significantly altered, furthermore, peak moment on the loaded limb will be greater when compared with the unloaded limb;

h) the alterations caused by both high-heeled shoes and load carriage will be remarkably greater than that caused by either high-heeled shoes or load carriage alone.

Furthermore, participants in the novice group will demonstrate above listed changes to a greater extent when compared to those in the experienced group. The experienced group was expected to show some types of compensatory movement to achieve more stable gait and posture patterns that are embedded in their walking pattern through adaptation.

1.4 Relevancy

The effect of either heel height or load carriage would cause a compensatory postural adjustment differently; however, the combined effect on posture is unclear. Previous studies supporting the idea of combined effect of both shoes and load are limited. However, literatures from biomechanics, gait, and posture, numerous studies focused on either impacts of shoes or load on gait can be found. Most of these studies were carried out with a purpose to better understand the altered gait to find a main cause of falls or posture problems among females since fall injuries and number of females complaints from postural problems have increased (Tencer et al., 2004; Ucanok & Peterson, 2006). Literatures studied effects of shoes have reported that types of shoes, heel heights, and types of shoes materials as well as shoe construction and literatures studied effects of loads have reported that loading style and loading weight are responsible for complaints from incorrect postures due to shoes or load carriage (Crosbie et al., 1994; Li, Hong, & Robinson, 2003; Menant, Steele, Menz, Munro, & Lord, 2008; Speksnijder, Munckhof, Moonen, & Walenkamp, 2005;). In reality, it is popular that women wear high-heeled shoes while carrying a purse on one shoulder. Therefore, studying the effects of shoes and load carriage together on the gait pattern and static postural stability may provide a better understanding. This understanding may be helpful for reducing musculoskeletal injuries or fall. Each segments in a body moves differently yet it all works together in increased degrees of freedom, it is important to look at the external influences combined when studying a human gait.

Esenyel et al. (2003) studied lower extremity joint function during the high-heeled gait and concluded that because of large muscle moments and increased work occurring at the hip and knee high-heeled shoes may predispose long-term wearers of high-heeled shoes to musculoskeletal pain. Poterio-Filho et al. (2006) also agreed with Esenyel et al. (2003) in their study on the effect of walking with high-heeled shoes on the leg venous pressure. Both studies conceded that long-term high-heeled shoes wearers are more prone to deleterious consequences such as musculoskeletal pain. It is necessary to study the difference between the experienced high-heeled shoes wearers versus novice high-heeled shoes wearers to confirm the results from previous literatures. The between-subject comparative study could offer an understanding on the biomechanical consequences of wearing high-heeled shoes and further on the postural adaptation.

An understanding of the combined effect of high-heeled shoes and load carriage during gait may help to determine the cause of musculoskeletal problems such as knee pain among young women who regularly wear high-heeled shoes and high falling rate. Mistakenly, it is often thought among general population that the high-heeled shoes put stresses on the foot however it could possibly cause damage to the ankle, knee, and back as well. The occurring problems in lower extremities contribute to approximately $3.5 billion spent annually in United States for woman’s foot surgeries which cause them to lose 15 million work days yearly (Payne, 2007). Helpful recommendations on shoe height and load weight for healthy posture and stability to reduce musculoskeletal disorders can be made for high-heeled shoes wearers those who work in service industries and require wearing high-heeled shoes for long period of time such as flight attendants or sales associates. The high falling rate and the threatening consequences indicate important needs for an understanding of biomechanics, the identification of the risk factors and the development of preventive strategies. Through biomechanical studies on the high-heeled shoes and load carriage during the gait, the prominent problems, if any, may be found and locomotor adaptation strategies may be suggested further. With better understanding more scientific comments to educate and to aid for reducing any related injuries could be generated for high-heeled shoes wearers.

1.4 Assumptions

The study has the following assumptions:

1. Repetitive trials during the experiment are not enough to transform novice participants into experienced in wearing high-heeled shoes.
2. The normal unloaded and 0 cm heel height gait at a self-selected speed on ground conditions is the most stable form of gait when compared with the loaded, high-heeled or both combined gait.
3. All participants have symmetry of gait in frontal plane. Since the study will be conducted with healthy participants, it is believed that it is safe to assume symmetry of gait.

1.5 Definitions

The following terms and definitions were used for the present study:

1. High-heeled shoes: Footwear designed for women that has a stiletto (pin shaped) heel which significantly raises the heel of the participant's foot higher than the forefoot.
2. Posture: A position of the body or of body parts
3. Balance: The ability to maintain the body’s centre of gravity within the limits of stability as determined by the base of support (Yim-Chiplis & Talbot, 2000).
4. Healthy: A participant with no previous history of musculoskeletal injury.
5. Stride length: Distance in meters of the point of the right heel contact to the next right heel contact.
6. Cadence: Number of steps per minute.

7. Self-selected walking velocity: A speed of walking which participants consciously choose to minimize the stress and maximize the comforts. This is measured in m/sec.

8. Double stance time: A period of time when both feet are in contact with the ground. This occurs at the beginning and end of the stance phase.

9. Single Stance time: A period of time when only one foot is in contact with the ground. In normal gait, it is equal to the swing phase of the opposite limb.

Chapter 2: Review of Literature

2.1 Introduction

Simple movements such as locomotion can be carried on from step to step unconsciously. Balance is managed throughout the movements in activities by nervous and musculoskeletal systems, however, it is not conceived until one faces a danger of falling or slipping. The neuromuscular and musculoskeletal systems work in harmony to keep a stable posture during standing and gait. Therefore, a postural control in correspondence with its environment is required to prevent a fall. This postural control is challenged as external environment changes, for example, an addition of load carriage, an increasing of heel-height, or both conditions combined. Load carriage is a common daily activity carried by many women in North America that alters the posture during the gait (Kinishita, 1985). High-heeled gait causes posture disturbance, which results in a higher falling rate among women in North America (Melton, 1995). Consequently, understanding the postural challenged gait from external constraints such as loads and heel-height may be beneficial. A biomechanical study on the postural changes can add the understanding in the balance mechanism of the musculoskeletal systems to maximize the stability of the body during dynamic environments. In this review, the factors disturbing gait and posture such as load carriage and shoes will be discussed briefly.

2.2 Gait and Posture Stability

Walking is body’s natural means of moving from one location to another. Walking forward on a level ground is the basic locomotion pattern. It uses a repetitious sequence of limb motion to move the body forward while simultaneously maintaining the stability (Perry, 1992). A sound knowledge of the characteristics of normal gait will provide a guideline to study further various complex gaits and to accurately detect and interpret deviations from normal gait pattern. Normal gait is defined by a stable movement of a locomotor unit in purpose to carry a passenger unit to a desired location. The locomotor unit consists of two lower extremities and pelvis that are directly contribute to the act of walking and the passenger unit consists of head, neck, trunk, and arms. The ability to assume an upright posture and maintain balance, the ability to initiate and maintain rhythmic stepping, and the ability to generate muscle strength accordingly are the essentials in walking (Perry, 1992). Normal walking satisfies these essential requirements efficiently and effectively in various environments. Through the gait analysis along with the sound knowledge on the normal gait, it is possible to study the gait altering factors. The effect of intrinsic factors such as medical conditions or diseases or extrinsic factors such as types of shoes, extra loads, or walking surfaces could be scrutinized. Thus, an assessment of motor pattern during walking could be a powerful tool for the diagnosis of pathological or abnormal gait.

The dynamic postural response to applied or volitional perturbations is called ‘postural stability’ (Prieto, Myklebust, & Myklebust, 1993). Postural stability is a foundation of individual’s ability to stand and to walk independently. It determines one’s ability to keep balance. Impaired balance has been correlated with an increased risk of fall (Melzer, Benjuya, & Kaplanski, 2004). Deteriorations in postural stability and the gait abnormality can be a major cause for falls, especially among elder population. Therefore, the postural stability is an essential component in assessing the ability to balance during various physical activities and the efficiency of interventions for improving balance (Berg, Wood-Dauphinese, Williams, & Maki, 2004).

The solid knowledge on the normal gait and postural stability could be used to study the high-heeled and loaded gait. Those external factors together may have destructive effect on postural stability since these factors are viewed as a stability barrier. For the further analysis of stability, the center of mass and rhythmicity will be discussed briefly.

2.2.1 Centre of Mass (COM) and Centre of Pressure (COP)

Quantification of the displacement of centre of mass (COM) and centre of pressure (COP) has been suggested to be a useful measurement to provide valuable insight into balance and postural stability in healthy or balance-challenged individuals.

A COM is one of the determinants of postural stability. COM must fall within the base of support for the balanced standing. However, during gait, the COM location and displacement are not restricted within the area of the base of support. During the normal gait, the COM moves in a pattern of sinusoidal. At the mid stance the COM reaches upward and laterally then moves down as the initial contact of the opposite limb (Fig. 2) (Perry 1992). This sinusoidal pattern is expected to be smooth throughout the gait.

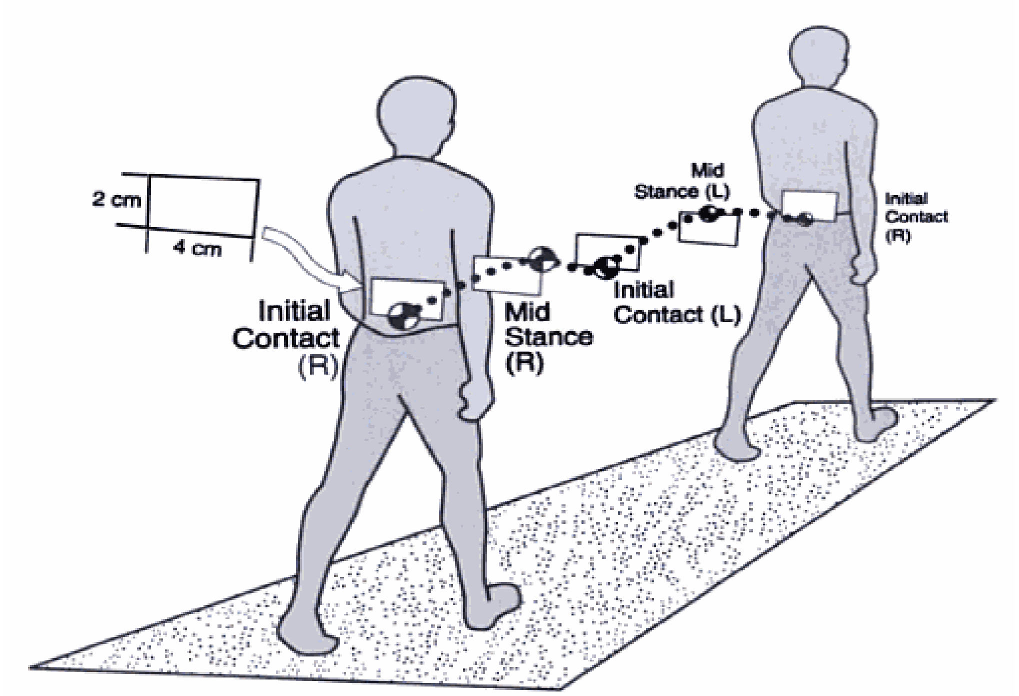

Fig 1. The excursion of centre of mass during one gait cycle from normal gait (Perry, 1992, pg 42).

The body's COM displacement must stay optimal throughout the gait to prevent a fall. Poor coordination of joint kinematic, limiting sensory information, deficient equilibrium reaction, and lacking muscle co-contraction affect the shifting of COM from one foot to the other in locomotion as well as during the quiet stance. Thus, if high-heeled shoes, load carriage, or both conditions together cause changes in the shifting of COM during gait the maintaining of the balance will be challenged and compensational movement must be done to correct the changes. A change in shifting of COM could be measured by COM displacement or COM velocity during the gait analysis to understand the effect of shoes or load. Iqbal and Pai (2000) and Pai and Patton (1997) introduced models explaining the measure of postural stability with COM and its velocity. Pai and his colleagues (2000, 1997) suggested that with COM excursion and velocity the measure for the degree of stability may be achieved.

A COP is a combination of inertial forces one uses to restore equilibrium. Tracking COP during the stance phase could provide information on the balance and pattern of progression. Kotah et al. (1983) reported that the participants wearing high-heeled shoes demonstrated greater variation in COP patterns, especially in the hindfoot and forefoot region. This finding is confirmed by other studies (Nigg et al., 2006) over time. Chisholm, Perry, & McIlroy (2008) reported that greater COP variability is shown among participants with asymmetrical gait and poor motor control. When compared with other studies, it could be said that COP variability resulted from a raised heel demonstrated a similar walking pattern as asymmetrical gait.

2.2.2 Rhythmicity

Rhythmicity, a smoothness of the gait cycle, is a fundamental property of the human motor system (Thelen, 1995). Hence, as long as the person keeps her rhythmicity stable during walking the posture problem would decrease. The goals are to shorten the time of adaptation and reach the level of normal rhythmic locomotion as well as to develop muscle strengths and in turn minimize the posture problems or falls.

Thelen's scheme of rithmicity can be explained by the smoothness of an acceleration pattern during gait. An acceleration pattern is defined by the degree of rhythm of the acceleration signal. Since the unit measurement of continuous walking is a stride, a stable rhythmic gait pattern should consist of acceleration patterns that repeat in multiples of two within any given stride (Menz et al., 2003). The selection of reference point on the trunk and head is based on the assumption that the task of maintaining stability when walking primarily requires first controlling the motion of the centre of mass at trunk and second optimizing conditions for visual apparatus at head (Menz et al., 2003).

In a study with hundred older participants using head and pelvic acceleration patterns to test gait stability, Menz et al. (2003) concluded that participants categorized as faller –this is done by reviewing each participants' previous history of falling to classify them into either faller or non-faller– showed uneven and irregular patterns when compared to non-fallers' smooth rhythmic pattern. According to other similar accelerographic analysis, the irregular patterns of vertical and antero-posterior acceleration at pelvis and head were evident in normal participants in walking with plaster casts and clutches (Smidth, Arora, & Johnston, 1971), in amputees walking with prosthetic limbs (Robinson, Smidth, & Arora, 1977), and in older people with balance problems (Yack & Berger, 1993).

It is unknown whether a high-heeled gait, asymmetrically loaded gait, or both conditions combined gait would produce changed head and pelvis acceleration patterns. High-heeled gait may produce a similar result as balance-challenged older participants because elevated gait challenges the walking balance. Asymmetrically loaded gait may resemble the result from those participants with plaster casts or prosthetic limbs because added loads on one shoulder stresses one side of the body.

2.3. Loaded Gait

A load carriage changes the centre of mass (COM) of the locomotor system, therefore to keep the balance during walking, a gait adjustment is a must in order to compensate this change. Previous studies on the load carriage have suggested that adding a load to the normal gait caused significant kinematic changes (Harman et al., 2000; Martin & Nelson, 1986; Pascoe et al., 1997). Holewijn and Lotens (1992) studied the influence of the load carriage on physical performance such as obstacle course, jumping, running, sprinting, throwing, and mobility test and concluded that the average loss of maximal physical performance was 1% per kg mass and 0.2 per litre backpack volume. Any biomechanical changes made due to the extra load will alter one's posture and muscle activities during locomotion as well as physical performances. A prolonged excursion of altered posture may lead to musculoskeletal problems.

2.3.1. Loaded Gait: Kinematic Effects

Lower Extremities Kinematics

Kinoshita (1985) investigated the effects of different loads of 0%, 20% and 40% of body mass among healthy male participants. A kinematic analysis of body-segment orientations and joint angles revealed a greater knee flexion that accompanied by a lesser hip extension for load conditions during the initial weight-bearing phase. The foot was rotated antero-postreiorly around the distal end of the metatarsal bones for a longer period of time when the heavy load was carried. Martin & Nelson (1986) also suggested the antero-posterior foot rotation emerged among participants when loading was added in their gait. During the gait, the balance is maintained through intact shift of center of mass from one segment to the other. Lower extremities must mitigate the kinematic changes caused by the load carriage.

However, it is questionable whether the high-heeled shoes assist or exacerbate the balance mechanism when it is combined with the loads.

Temporospatial gait parameters

Gait analysis is an objective method for quantification of musculoskeletal system function during movement. From previous studies on the load carriage, it is well suggested that temporospatial gait parameters from the loaded gait were significantly different from that of normal gait (Crosbie et al., 1994; Harman et al., 2000; Kinoshita, 1985; Knapik et al., 1996; Pascoe et al., 1997). A study done by Kinoshita (1985) with adult participants, an increase in stride frequency and decrease in stride length were evident. Double stance time increased while single stance time decreased as load increases from 0 to 40% of body mass. Also, with an increase in double stance time the self-selected velocity was reduced with load carriage for the stable gait. A load carriage study with children by Pascoe et al. (1997) suggested when participants carried 17% body mass the stride length significantly decreased and the stride frequency significantly increased compared to no load conditions. During the simple locomotion without a load, the purpose of the movement is to travel to a desired location but when a load is added the purpose of the movement is to deliver the load. During loaded gait, the body works to serve its purpose which is different from simple walking, thus, evidences of changes in temporospatial parameters presented from previous studies are expectable. The changes in temporospatial gait parameters with load have suggested that in order to maintain the balance and efficiency during loaded locomotion the body needs to compensate changes.

2.3.2. Loaded Gait: Kinetic Effects

Lower Extremity Kinetics

LaFiandra et al. (2002) reported that contrary to the increase in the upper body torque the 40% BW backpack resulted in a decrease in lower body torque. Contradicting results were generated by Harman et al. (2000) from their military load carriage study. The torques about the ankle, knee, and hip clearly increased with load over the stride with different degree in different joints. Knee torque showed the large increase in which twice that expected from the change in load alone in extension torque. Hip extension and ankle plantarflexion torque were proportional to the load increase.

The increased load carriage in backpacks raised ground reaction forces in proportion to the total mass. Peak forces changed with loads as low as 20 kg and the forces necessary for balance increase significantly when any load is carried (Tilbury-Davis & Hooper, 1999). This notion is supported by other study. Kellis and Arampatzi (2009) concluded from their study with different types of carrying method among student participants that carrying a schoolbag of 17% body weight alters the GRF characteristics of gait.

2.3.3 Effect of Asymmetric Loading on Gait and Posture

It has been well documented and reviewed from previous studies that a front-back loading is a most efficient way of carrying load during gait, especially with heavy loads (Holewijn & Lotens, 1992; Kinoshita, 1985; Legg & Mahanty, 1985). However, the front-back loading is not a popular method used among many women. Asymmetrical load carriage such as woman’s purse has a different impact on gait pattern when compared to symmetrical load carriage such as backpack. Hong & Li (2004) studied thirteen children in stair walking with two types of carrying method, a backpack and one-strap sports bag. Hong & Li found that during stair ascending the critical load that requires more stable gait pattern was smaller for the athletic bag worn on one shoulder for 10% of body mass compared to backpack for 15% of body mass. The critical load weight induced a significant increase in stance and double support time. A similar study was done with female college students by Smith et al.

(2005). Smith et al. examined the effect of carrying a backpack either bilaterally or unilaterally on trunk biomechanics and concluded that the unilateral carriage such as a hand-held or one shoulder carriage caused a significant lateral spinal bending, shoulder elevation, and increase in pelvic tilt or forward lean. Because the load is more likely to move as one unit with the trunk, the unilaterally-carried-load would possibly disturb the dynamic stability to a greater extent than the bilaterally-carried-load and disrupt the smoothness of gait cycle. The consensus of such conclusion was also expressed by Pascoe et al. (1997) and Legg et al. (1985). Lateral flexion toward the contralateral side of the load was evident from participants with load during walking. As a result, a contralaterally shifted COM was induced by the side loading (Choi et al., 2007). This is a compensatory postural adjustment to keep the upright posture since a gravitational force from the heavy load on hand pulls the arm inferiorly on only one side. Crosbie et al. (1994) studied effect of the side loading carried on one hand and agreed with the observations on temporospatical parameters from asymmetrical load carriage on shoulder. Stride length and single stance time showed a significant decrease with added load. Furthermore, the asymmetrical loading changes joint kinetics. Choi et al. (2007) reported that when compared with unloading side, the loading side showed a greater ankle plantar flexion moment, knee extension moment, and hip extension moment.

In summary, the asymmetrical load carriage altered gait pattern, most profoundly the trunk kinematics. The changes by asymmetrical loading may be exacerbated further with raised heel height from the high-heeled shoes.

2.4 High-heeled Gait

The type of shoes influences the balance and muscular activity during walking. A gait deviated from a normal gait may have factors detrimental to balance during walking (Perry et al., 2006), soft tissue damage (Seroussi, Gitter, & Czerniecki, 1996), or muscle fatigue

(Barton, Coyle, & Tinley, 2008). Specifically, a high-heeled shoe was found to alter the gait pattern. The effect of high-heeled shoes on biomechanics will be briefly reviewed in this section.

2.4.1 High-heeled Gait: Kinematic Effects

Lower Extremity Kinematics

A prevalence of 83% of foot problems in women aged between 50 and 70 occurs from wearing high-heeled shoes (Speksnijder et al., 2005). High-heeled shoes alter three-dimensional kinematics on lower extremities during locomotion. While wearing the high-heeled shoes, female participants displayed an increased in plantarflexion during walking. The plantarflexion particularly at heel strike and toe-off showed significant increase (Ebbeling, Hamill, & Crussemeyer, 1994; Stefanyshyn et al., 2000; Snow & Williams, 1994; Ucanok & Peterson, 2006). Along with excess plantarflexion, there was a trend toward decreased eversion (pronatoin) as heel height increased (Hsue & Sue, 2009; Snow & Williams, 1994; Stefanyshyn et al., 2000). In addition, a trend of decreased tibial rotation as heel height increased was evidenced. Inman (1976) elucidated that the decrease in tibial rotation may be a result of the coupling mechanism between the foot and lower leg.

Wearing high-heeled shoes significantly alter the function of ankle and to compromise any changes at ankle, knee and hip, yet mostly the knee, must compensate to maintain stability and progression during walking. Ucanok and Peterson (2006) reported that the maximum knee flexion angle was greater with increased heel height. Other studies examined knee joint kinematics also supported Ucanok and Peterson (Ebbeling et al., 1994; Murray, Kory, & Sepic, 1970; Opila-Correia, 1990; Snow & Williams, 1994).

High-heeled gait alters at hip joint and is no exception. A study examines the effect of high-heeled shoes on normal and pregnant women by Anderson, Gamble, and Noronha (2008) revealed that the hip flexion angle during the stance phase significantly increased with heel height of 8.3 cm regardless of the pregnancy status. However, Murray et al. (1970) and Opila-Correia (1990) found the opposite results. Two studies concluded that the hip flexion angle increased during swing phase and no difference during the stance phase. Ebbeling et al. (1994) reported no change in the hip angle while Esenyel et al. (2003) reported an increased hip joint adduction during stance phase. Many previous studies have looked at the kinematics of lower extremities but paid little attention to hip joint. It could be assumed that alteration at the ankle joint due to raised heel mostly affects the knee joints and at the knee level most of the compensational work is done. De Lateur et al. (1999) agreed with this notion. They studied both negative and positive heeled shoes and found there was no significant trend in the hip and trunk and concluded that the greatest compensation for the raised heel height occurs at the distal end joints.

Lower extremities, specifically the distal joints, affected the most by shoes. During gait, ankle, knee, and hip angles undergo various changes to stabilize the upper body and to work together for the compensation purposes. It is natural that for any changes at ankle joint influence the knee and hip as the body is a kinetic chain.

Temporospatial Parameters

Numerous studies on high-heeled shoes disclose different results. The changes in temporospatial parameters due to high-heeled shoes subsist not solely due to its height but its characteristics such as sole rigidity and general shoes design.

Eisenhardt et al. (1995), Esenyel et al. (2003), Gastwirth, O’Brian, Nelson, Manger, & Kindig (1991), and Ucanok & Peterson (2006) all agreed in their findings that gradual decrease in stance duration was occurred as the heel height increased. Since the stance duration is directly related to the cadence, a decrease in cadence to maintain balance was resulted. From the study on the effect of walking surface and footwear, Menant et al. (2008) found that the elevated heel shoes elicited reduced walking velocity and increased double support time. A significant decrease in walking velocity and an increase in double support time suggest a decrease in stability. In addition, the heel horizontal velocity at heel strike was found to be greater when compared to no heeled shoes. This would predispose individuals to initiating a slip when walking on slippery surfaces. Decrease in gait cycle and stride length as heel height increases also widely suggested from numerous previous studies (de Lateur et al., 1999; Esenyel et al., 2003; Katoh, Chao, Laughman, Schneider, & Morrey, 1983; Ucanok & Peterson, 2006). Study results in the high-heeled gait kinematics have shown the raised heel provides a limited stability during gait among young and old participants.

2.4.2 High-heeled Gait: Kinetic Effects

Specific joint forces and moments are related to the measures of altered or pathological gait or movement. Walking in high-heeled shoes produces changes in lower extremity joint kinetics that are associated with the altered joint kinematics as reviewed in previous section. Hsue and Sue (2009) reported from high-heeled gait study with young and elder participations that the heel height has greater effect on the joint forces and moments and the differences were found in all lower extremity joints. However, even with the evidence showing the changes in kinetic parameters and the information that kinetic analysis could offer, the studies on kinetic parameters during high-heeled gait are limited.

Lower Extremity Kinetics

Esenyel et al. (2003) compared a high-heeled gait to a low-heeled gait and found the ankle moment was significantly reduced during high-heeled gait due to the increased plantar flexion angle. The decrease in ankle moment was evident from other studies (Stefanyshyn et al., 2000; Hsue & Sue, 2009). It can be concluded that the increased plantarflexion when walking in high-heeled shoes requires a smaller propulsive moment to take-off because plantarflexion causes the forefoot lever arm to shorten, moving the ground reaction force closer to the ankle and lessening the restraining plantar flexor moment demand.

Increased heel height increased the knee moment (Esenyel et al., 2003) and peak abduction moment at the knee (Hsue and Sue, 2009). The increase in the knee moment stabilizes the joint. The need for the increased knee moment is because the use of a higher heel increases the floor-to-knee distance, thereby increasing the tibial lever arm through which the posteriorly directed ground reaction force flexes the knee.

At the hip, adduction moment magnitude increased and the duration of hip flexor muscle moment was prolonged, leading to an increase in overall muscle work (Esenyel et al., 2003). The increased hip adduction moment can be explained by the increased hip joint adduction which moves the hip laterally relative to the foot and contributes to a medial shift in the location of the centre of pressure. The more medially placed ground reaction force creates a larger knee varus moment and hip adduction moment. The prolongation leads to an increase in the overall concentric work of the proximal hip flexor muscles.

2.4.3 Influencing Factors of Gait and Posture Stability

Base of Support

Foot must overcome all the stresses it received from the upper body in order to stabilize during gait. With larger or broader base of support, the centre of the gravity is able to fall within it easily and in turn prevent the system from falling. Therefore, techniques such as spreading foot apart or lowering the body’s centre of gravity in effort to prevent a fall by setting the centre of gravity within the base of support are often used to gain stability, especially in sports. Balance during gait differs from during standing in which the centre of gravity moves constantly beyond base of support. However, simple techniques to increase stability that were implemented during quiet standing cannot be effectively used during walking. In order to initiate a walk, centre of gravity must be accelerated in a forward direction ahead of the base of support. This movement of COM is commenced by the voluntary initiation to start a forward fall. The reverse is true during termination of gait where the centre of gravity must return within the base of support (Winter, 1995).

The nature of the foot, being relatively small and narrow width, diminishes stability as it provides limited area for the centre of gravity to fall within. Due to the structural disadvantage of the foot, stabilization during the gait relies on a balance mechanism. Baudy and Kuo (2000) suggested that preventing the system from a fall is retained through passive stability in the plane of progression that is done at limb level and active control lateral stability that cannot be obtained at limb level alone. Therefore the challenge during walking is to keep the lateral stability because it requires more cognitive attention. Having a smaller base of support, especially small based shoes like high-heeled shoes, challenges this aspect. Therefore, having a larger sole with greater contacting area offers advantage in stability. Older participants with high-heeled shoes greater than 2.5cm nearly doubled the risk of falling (Tencer et al. 2004). The potential to tip sideways due to a poor lateral stability is the main contribution to increased falling rate.

Shoe Material

Shoe material plays an important role in balance and stability. There is a controversy over whether soft material provides better stability due to its shock absorption ability or rigid material for its stable support. From the numerous studies on stability and shoe material, Robbins, Waked, and Krouglicof (1998) suggested that destabilizing footwear have soft, thick, and highly resilient sole. Robbins et al. (1998) tested the assumption that shoes made with a sole material that retains compressed thickness between steps (low resiliency) provide better balance than and comfort equal to shoes composed of high resiliency sole material and found accuracy in this assumption. A contradicting result was found from a balance study with different hardness of the sole done by Lord, Bashford, Howland, and Munroe (1999). Lord et al. found that a height of the collar of the shoes at ankle level was an indicator for the stability not the materials' hardness of the sole.

The material for the sole of shoes must contact with the ground well, such materials made as non-slip and rough material is ideal. Whether the materials commonly used for high-heeled shoes provide enough strength to increase the stability is questionable at this stage of study, so the ability to prevail over such material problem to keep its stability is something high-heeled shoes wearer must face.

2.5 Combined effects of High-heeled shoes and Load carriage

It is well stated from previous studies introduced previous sections that high-heeled shoes or load carriage alone influence the normal gait among variety participants. When both high-heeled shoes and load carriage are introduced, any necessary biomechanical changes made for adaption to prevent fall might be more severe than when body is affected by either high-heeled shoes or load carriage alone. For example, deformation at lower extremities due to wearing high-heeled shoes can be exacerbated when extra load is added presenting greater stress. At the foot, increasing load causes increased dorsiflexion at the toe-off (Harmean et al. 2000). This exposes metatarsal bones to greater and more prolonged mechanical stress, possibly accounting for the incidence of stress fracture of the foot among backpackers and soldiers. Any biomechanical problem created by load carriage does not only affect nearby segments such as shoulder or back, but can be a root to a problem at the foot or any other segments. Any deleterious problem formed either from heel height or load carriage could be compensated or aggravated by its external disturbances. It is significant to study the combined effect to the body for further understanding of postural stability.

However, despite the number of studies that have addressed the effects of high-heeled shoes or effects of various load carriage on balance and gait, there are no studies has been done to look at two conditions together. The available evidences pertaining to high-heeled shoes alone and load carriage alone are sufficient, yet it is erroneous to conclude how those two add up and influence the gait and stability by looking at previous separated studies. From the combined study it can add the understanding on how the balance is kept by compensating changes caused by high-heeled shoes or load carriage more accurately because two external disturbances –high-heeled shoes and load carriage– are combined to persuade the gait at the same time.

Chapter 3: Methodology

3.1 Participants

Based on the data from a pilot study (Lee & Li, 2008), total sample size was estimated to be 26 for the minimal statistical power of 80% using GPower software (Erdfelder, Faul, & Buchner, 1996). Thirty females aged from 18 to 30 years old were recruited as a participant for the present study. Participants older than 30 years old were excluded since with increasing age pressure loading of the third, fourth, and fifth metatarsals increases (Hutton & Dhanendran, 1981), and this may present an age effect to the high-heeled or loaded gait. Participants with no previous musculoskeletal and neurological injury were recruited. All the recruited participants had a body mass index (BMI) in normal range from 18.5 to 24.5. This was to eliminate any possible factors, if any, to influence the high-heeled gait and its postural stability.

For the purpose of the present study, two different types of participants were recruited; novice and experienced in wearing high-heeled shoes. The grouping was done based on the experience of wearing high-heeled shoes. A novice is defined as someone who wears high-heeled shoes less than twice a month or has an experience of wearing high-heeled shoes less than three years. An experienced is defined as someone who wears high-heeled shoes more than twice a week or has an experience of wearing high-heeled shoes over three years. Fifteen participants were recruited for each group. A short questionnaire (Appendix 1) asking participants' previous histories of wearing high-heeled shoes was given at the recruitment stage to aid determining participant type. This process was helpful to recruit the same number of participants for each group. The questionnaire asked for frequency, number of years, and self-confidence level of wearing high-heeled shoes as well as which type of high-heeled shoes the participant often wears. If difficulty in determining the participant type arose with such participant, she was excluded from the study.

3.2 Instruments

Bags and carrying load

A small women's purse sized 26.7 cm (L) x 3.8 cm (W) x 16.5 cm (H), manufactured by LeSportsac Inc. (model: 7606 Lulu, Le Sportsac Inc.) was used in the study. The bag was made of nylon and weighted 0.030 kg (Figure 3). The strap was 22.0 cm (L) x 1.1 cm (W) and is not adjustable. Narrow width of the strap allowed itself to be sat on participants shoulder without contacting reflective marker placed on the acromion. The body of the bag was placed between the trunk and upper arm. Such bag was selected to be used for the testing because of its light weight that causes no hindrance when a load is added to the bag.

Metal weights of 2.0 kg, 1.0 kg, 0.5 kg, and 0.1 kg were used as loads and were placed into the purse. The metal weights were circular discs, with diameters measured from 12.5 cm for 2.0 kg to 3.0 cm for 0.1 kg. To prevent the phenomena of the hard edge of metal weight hurting participants during walking, the weights were covered by soft fabrics while the weight of the fabric was minimized for no interference to the test. These metal weights were used to create necessary body weight according to each participant's body weight (BW). 0%, 5%, and 10% of BW were prepared for the test. Ten percent of BW was set as a maximum weight because numerous load carriage studies have suggested that the 10% of body mass is the critical mass that alters the gait and balance and showed significant effects on participants when carried on one shoulder (Hong & Li, 2004).

Shoes

All the participants wore the same styles of two pairs of high-heeled shoes manufactured by Nine West (Jones Apparel Group Inc., NY, USA) and a pair of flat-heeled

Figure 2. Nylon purse with three dimensional measures in cm.

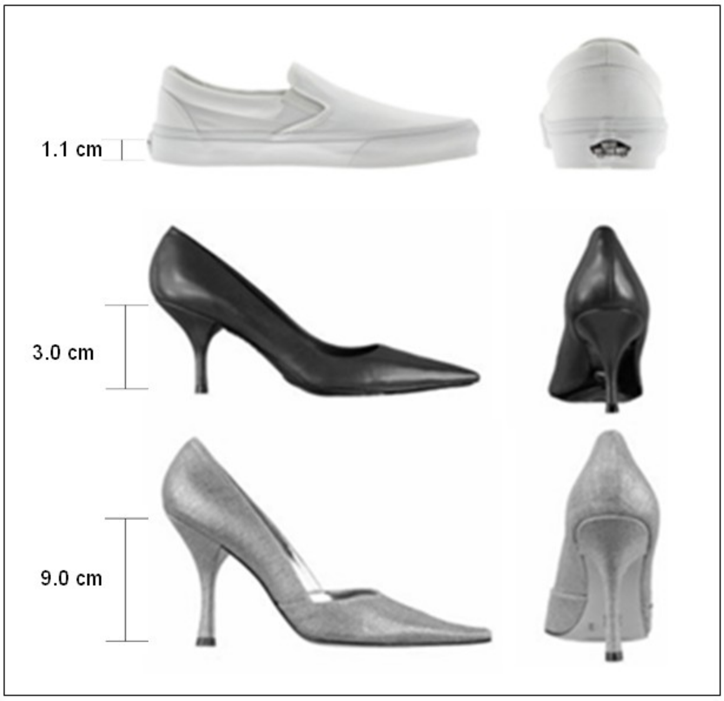

Figure 3. A pair of 1.1cm shoes represents flat-heeled shoes. Two pairs of high-heeled shoes with 3.0 cm and 9.0 cm stiletto heel were used.

shoes manufactured by Vans (Vans Inc., California, USA) (Figure 4). The flat-heeled shoes of 1.1 cm were used to serve as a control condition. Medium height was represented by a 3.0 cm high stiletto and maximum height was represented by a 9.0 cm high stiletto. The base of the support at the tip of stiletto heel was very small, 0.9 cm². The upper part of both high-heeled shoes was made of leather. Both shoes were prepared in woman's size 6.5, 7.5, and 9, which are arguably the most common shoe sizes in North America (Woolcreater, 2009).

Walking path

The testing area included a walking path surrounded by infrared cameras facing in. The walking path was approximately 8 m long. The calibrated volume within the total walking path was approximately 3 m was used for the study. The walking path had no marks or signs indicating the capturing volume. The floor was made out of rubber material providing slight cushioning.

Motion Analysis System

Motion recording was done for the walking trials to obtain kinematic and temporospatial data with Vicon Motion Analysis System (Vicon MX-13, Oxford Metrics, Oxford, UK) recording at 200 Hz. Nine infra-red, high-speed, optical cameras were used to capture three-dimensional views of participants. All cameras were either hung from the ceiling or mounted on individual tripods and strategically positioned around the testing area (Figure 5). The positioning of the cameras allowed all anatomically placed body markers to be clearly visible and accurately identified for further process. The views from all cameras were synchronized to capture the entire range of body movement during the walk. The system was calibrated prior to the testing in two parts; a dynamic calibration followed by a static calibration. The dynamic calibration was done using a T-shaped wand (240 mm) with three reflective markers. The wand was waved about to create a recording volume while letting each camera capture at least 3000 frames with the three markers visible. Then the static calibration followed. It was done with a L-shaped frame (ErgoCal, 14 mm) which set the origin of the global coordinate system by placement on the floor in the centre of the capture volume. The origin of the capture volume was calculated and X, Y, and Z axes were defined through static calibration. The X axis was the anterior-posterior direction of walking, Y axis was the medial-lateral direction, and Z axis was the vertically upwards direction. The calibration process strictly followed the manufacture's instruction manual from the Vicon Motion Analysis System (Vicon MX-13, Oxford Metrics, Oxford, UK).

Force Plates

For the kinetic data acquisition, three force plates (one model 9286AA, Kistler Instruments Corp, Winterhur, Swtz; two models FP 4060-08, Bertec Corporation, Columbus, OH, USA) were used in recording ground reaction force at 1000 Hz. The force plates were embedded in the middle of walkway in a row (Figure 5) in such a way that participants could step on each plate one after the other within their steps of walking.

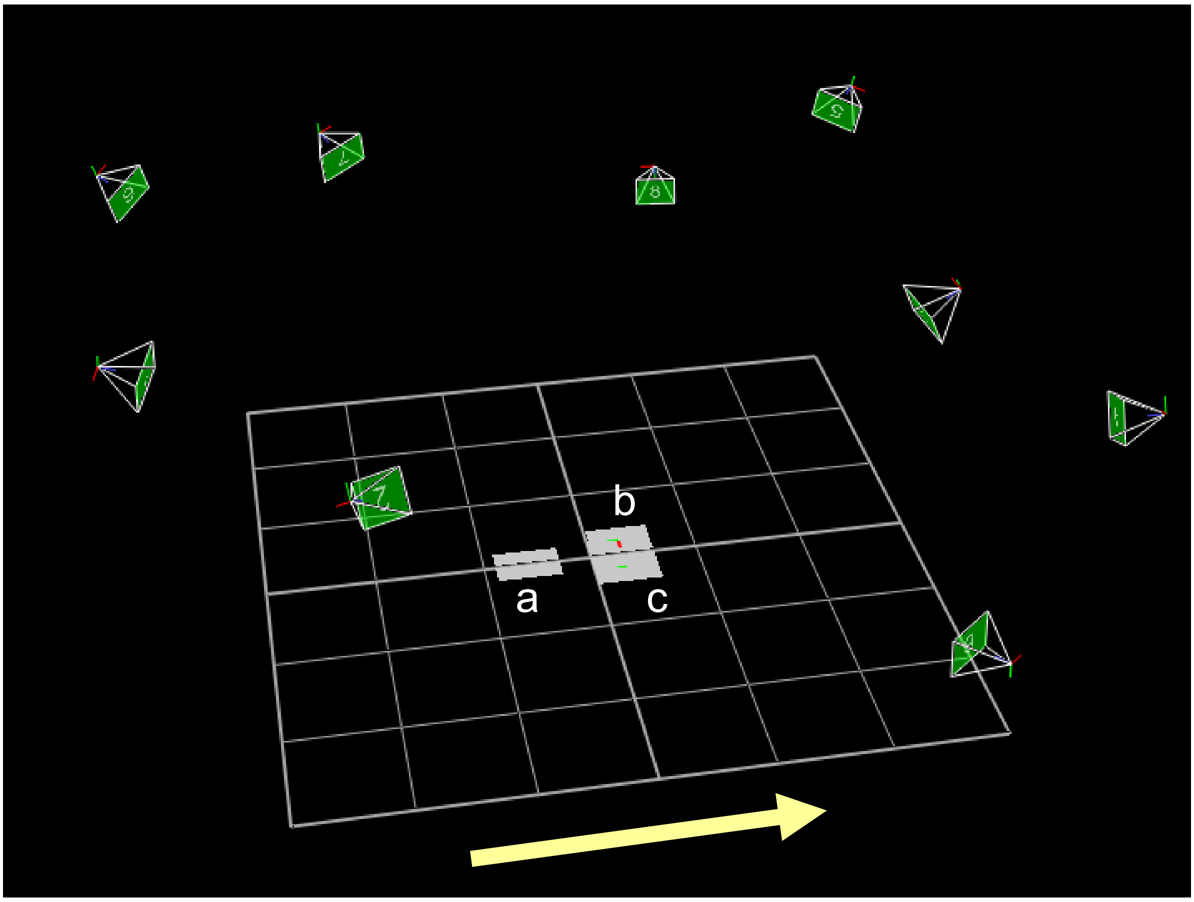

Figure 4. Three dimensional representation of the testing area with nine infra red cameras and three force plates (a: models 9286AA, Kistler Instruments Corp, Winterhur, Swtz; b & c: FP 4060-08, Bertec Corporation, Columbus, OH, USA). An arrow indicates the walking direction.

3.3 Participation Preparation Procedures

Prior to the start of testing, participants were given a detailed explanation of the purpose of the study and informed of the nature of present study as well as its procedure and design. A testing began after the participants signed a consent form. Complete anonymity and liberty to withdraw from the test were explained to all participants upon signing the consent form.

Participants were asked to remove all accessories and to change into a suit provided. Participants received tight black t-shirt, shorts, and two pairs of high-heeled shoes. A loaded purse was provided to participants once weights were prepared by the researcher after measuring her body weight. Each of the loaded conditions was prepared by calculating 0%, 5%, and 10% of the body mass. A percentage of body mass rather than an absolute weight was used for the testing to achieve normalization among participants. For the loading conditions, every participant wore the loaded purse on the right shoulder to simplify the data treatment and analysis. Upon a completion of the marker placement on participants, shoe fitting followed. Two pairs of high-heeled shoes, 3 and 9 cm high, and one pair of flat-heeled shoes were fit properly according to each participant's shoe size. Participants were asked to practice their walk for two to three minuets along the testing path to familiarize the experiment settings and to adapt to the high-heeled shoes and loaded purse. Practice was recommended especially to those in the novice group who has little experience in wearing high-heeled shoes. When requested by participants, a longer period of practice was granted.

Preparation of the marker set & electrodes on participants' body

Total of 43 reflective markers were placed on the participants by the researcher for the full body capture to collect kinematic data including temporospatial parameters. University of Ottawa Motion Analysis Model (UOMAM) marker set, a modified version of Plug-in-Gait model (VICON, Oxford Metrics, Oxford, UK) created by University of Ottawa

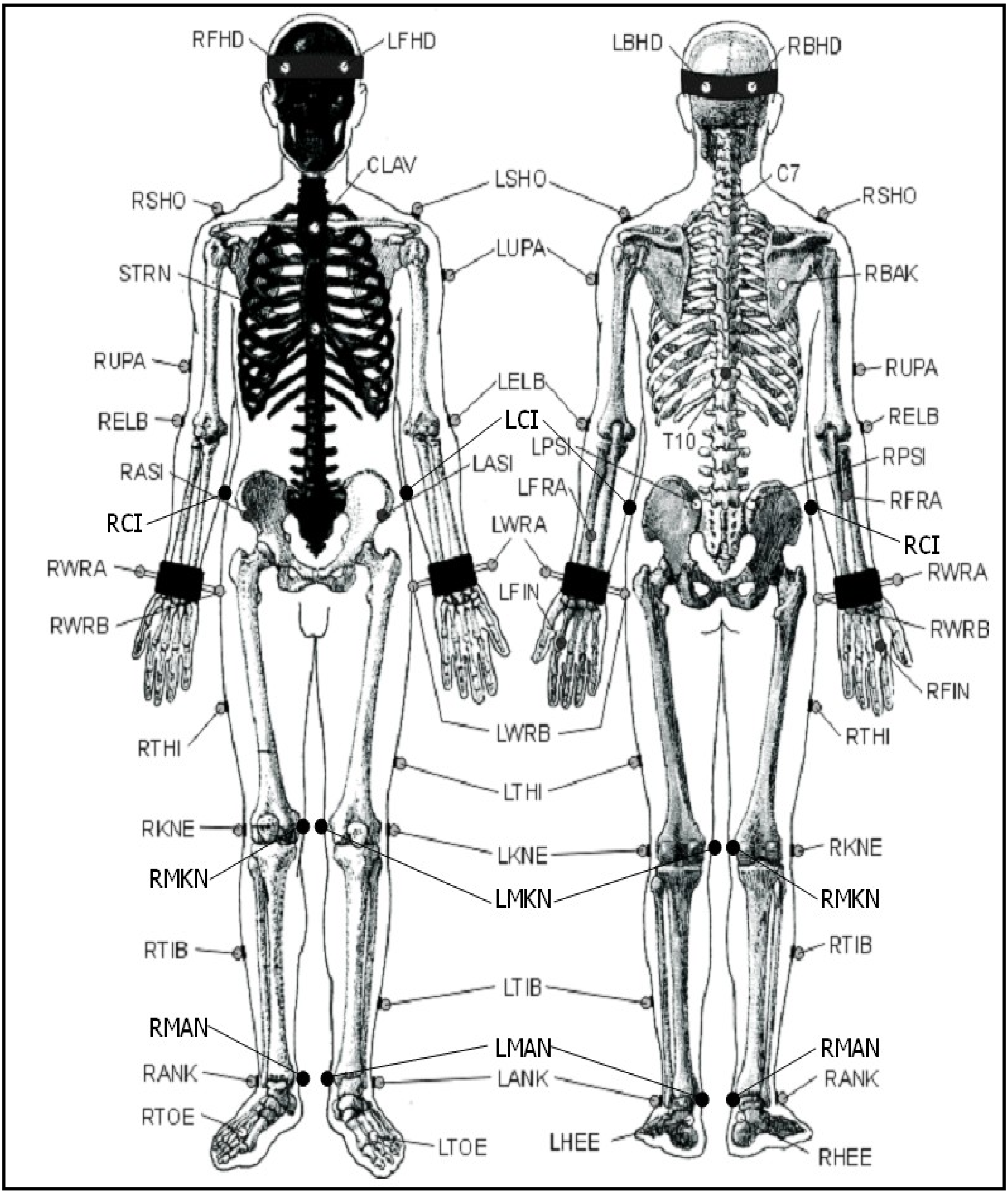

Figure 5. Anatomical landmarks of UOMAM marker set for the motion capture during data collection.

was adopted for the gait analysis (Figure 6). Originally UOMAM maker set has 45 makers, but marker RCI and LCI were omitted since current study tested a simple walking motion only. The main purpose of RCI and LCI markers are to locate the hip joint in the absence of LASI and RASI during sitting trials. All anatomical landmarks were identified through palpation. To distinguish between left and right side of the body, markers on the limbs were placed asymmetrically.

3.4 Testing Protocol and Data Collection

An Activities Specific Balance Confidence (ABC) scale (Powell & Myers, 1995) (Appendix 2) was given out to each participant to fill out. Through the Experience of High-heeled shoes Questionnaire (Appendix 1) that would have already been performed during the recruiting period the information on participants' age and footwear background were achieved and ready on the testing day. Additionally, height (cm), body mass (kg), foot size, and other anthropometric measurements (leg length (cm), knee width (cm), and ankle width (cm)) were measured and recorded after each participant put on the black experimental suits.

Static Balance Tests

Measures of static balance, one-leg stance tests and tandem stance tests, were performed prior to walking trials for every condition for every participant. Static balance measurement tests were performed together once each participant was. For the single leg stance test, participants were asked to stand only with one foot of her choice and hold the other foot near the mid-position of the supporting calf. The arms were folded across the chest. Participants were asked to stand still as long as possible with and without eyes closed. The time was recorded. A maximum time recorded was 60 seconds. The trial was terminated when participants failed to remain in the position. For the tandem stance test, participants were asked to stand heel-to-toe with her arms folding across the chest. A tandem standing is a static standing where a participant stands with the heel of the front foot of her choice touching the toe of the back foot in a straight line. This test was done with and without eyes closed. The testing protocol for tandem stance test was equivalent to the single stance test.

Static and Dynamic Motion Capture

Prior to arrival of participant in the laboratory, the static and dynamic calibrations of VICON system were done to minimize testing period for the participants.

A static trial of 5 seconds was performed to allow the cameras to pick up each of the reflective markers and create a 3D model of the participant using the VICON Motion System. One static trial was performed for the control condition.

The dynamic trials were executed next. The participant was asked to walk across the testing area where all the capturing cameras faced in creating a testing volume. At least eight steps were needed to be recorded within the 3 metres distance walking to achieve excellent reliability (Kernozek, LaMott, & Dancisak, 1996). The participant completed a minimum of five successive trials of each condition. The participant was asked to step on the force plates consecutively during walking without looking down. A successive trial was determined by the researcher, the participant should walk normally and naturally as if she is not being watched or recorded. In addition, a walking trial was deemed successful if the participant walked without a fall and any displacement of load on the shoulder. The participant walked at her preferred speed to best mimic real high-heeled-walking. There were total of nine different conditions with combinations of three different heights of the high-heeled shoes and three different weights of the load carriage in the experiment (Table 2). The testing was done in randomized order of conditions for each subject so that the results are in no way to be affected by any previous outcome. Participants were allowed to take a break at anytime during the experiment if muscle fatigue occurred or requested by the participants. Also, participants were allowed to withdraw from the experiment at anytime if requested.

Table 2. Description of different conditions and number of trials needed

	Conditions	Number of Trials
#1	0cm Height x 0% Weight	5
#2	0cm Height x 5% Weight	5
#3	0cm Height x 10% Weight	5
#4	3cm Height x 0% Weight	5
#5	3cm Height x 5% Weight	5
#6	3cm Height x 10% Weight	5
#7	9cm Height x 0% Weight	5
#8	9cm Height x 5% Weight	5
#9	9cm Height x 10% Weight	5

3.5 Data Processing and Analysis

The present study analyzed movements in three dimensions. Two consecutive strides for each right and left legs were analyzed.

Temporospatial and Kinematic Parameters

From VICON Nexus software (v1.3), all temporospatial data were normalized to gait cycle and presented based on gait cycle. Measurements of foot contact and toe-off were obtained by visually inspecting the position of the virtual markers on the heel and the toe. Step length was measured from heel to heel in the anterior-posterior direction and step width was measured from heel to heel in the medio-lateral direction. Single limb support was counted the time from contra-lateral foot off to contra-lateral foot contact. Double support phase counted the time during trail foot contact to leading foot toe-off.

VICON Nexus software (v1.3) along with UOMAM model was used to obtain lower-limb kinematic measurements of hip, knee, and ankle angles in frontal and sagittal planes. Computed joint angles from Nexus were exported to Excel (Microsoft, Washington, USA) to find a maximum and minimum angle, angle at heel-strike and toe-off for each trial.

Kinetic Parameters

The kinetics parameters were calculated through the inverse dynamics approach. By using the UOMAM model the moments of force and powers at each joint in sagittal and frontal planes were calculated from Vicon Nexus software (v1.3). Computed kinetics data were exported to Excel (Microsoft, Washington, USA) to find a maximum value and values at heel-strike and toe-off. Moments of force and powers were normalized to body mass to allow between subjects comparisons. Each trial was cropped and time-normalized to a 100% gait cycle and then averaged for five trials.

3.6 Statistical Analysis

Initially, the data were examined and inspected. Data from two trials of experienced group participants were excluded from the analysis since it were detected as outliers resulting from measurement error such as hidden markers. Data from five trials were averaged for each condition for each participant. Collected and processed data were analyzed using Statistical Package for Social Sciences (SPSS) version 16.0 software for Windows (SPSS Science, Chicago, Illinois). Values obtained for each variable were imported to SPSS to determine if there is a significant difference in any of variables tests.

Each dependent variable was compared between the Novice group and Experienced group. There were 9 different conditions since there were three levels in two dependent variables, hence, nine different t-tests were conducted to determine the difference between the groups. This t-test was done for all dependent variables.

A mixed design one way repeated measures analysis of variance (ANOVA) were conducted twice, one for each group, to determine the within group effects of height of the shoe and weight of the load on all dependent variables. When significant contrast resulted from an interaction of the independent variables, Tukey's Post-Hoc test was performed to further investigate the significant difference. For all statistical tests, the level of significance was set at $P < 0.05$. The result from the Experience status Questionnaire which consists of five questions was plotted in histogram and general pattern was established. Statistical analysis was performed among two different groups in their frequencies of wearing high-heeled shoes.

Chapter 4: Articles

4.1 Article 1

Combined effects of high-heeled shoes and asymmetrical load carriage on lower extremity kinematics during walking in healthy young women

4.2 Article 2

Effects of asymmetrical load carriage and high-heeled shoes on lower extremity joint kinetics in healthy young women during walking

4.3 Article 3

Combined effects of high-heeled shoes and load carriage on joint kinematics and kinetics of lower extremity during walking in experienced and novice high-heeled shoes wearers

Article 1

COMBINED EFFECTS OF HIGH-HEELED SHOES AND ASYMMETRICAL LOAD CARRIAGE ON LOWER EXTREMITY KINEMATICS DURING WALKING IN HEALTY YOUNG WOMEN

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Abstract

A within-subject comparative study of walking while wearing different heights of high-heeled shoes and different weights of asymmetrical load carriage was performed to identify and describe the changes in lower extremity joint kinematics associated with combined effect of shoes and load during level ground walking. A volunteer sample of 15 healthy young female habitual high-heeled shoes wearers underwent a quantitative measurement of temporospatial and kinematic parameters of hip, knee, and ankle on both loaded and unloaded limbs. High-heeled shoes and asymmetrically carried load together altered temporospatial parameters and joint kinematics during gait. With increased heel height and increased load weight, cadence decreased and stride length increased. Knee flexion angle increased with the raised heel height, and the load only served to exacerbate the changes. The changes in hip angle were mostly caused by the asymmetrical loading while changes in ankle angle were mostly caused by the raised heel height. In conclusion, the present study suggests that when high-heeled shoes and asymmetrically carried load are combined, the alterations made at each joint are much greater than that of high-heeled shoes or load carriage alone would cause.

INTRODUCTION

As a desire to look beautiful among women grows in North America, the number of women wearing high-heeled shoes has increased[1]. Surveys on shoe use have shown that 37% to 69% of women wear high-heeled shoes on a daily basis[2]. With an increased number of females wearing high-heeled shoes, numerous studies have been conducted to find its effect on body posture[3] and stability[4]. Footwear, a contact medium between the body and the ground, plays an important role as a shock absorber during walking. To improve the shock absorbing function at heel contact during walking, many researchers and manufactures put efforts in their shoe design and material engineering. However, high-heeled shoes, especially a pin-point heel called stiletto, does not offer cushioning at heel-strike but delivers the contact force to the body directly. In addition, the shoe's small base of support at its heel creates a larger peak force at heel-strike and reduces stability especially when walking on uneven surfaces[5]. Poor footwear has been reported to be a main cause of a fall among female population, and high-heeled shoes are often deprecated by orthopaedic physicians due to joint complications. Previous studies with different heel heights documented significant changes in the lower extremities joint kinematics. Gait analysis revealed that the ankle plantarflexion, knee flexion, and hip flexion angle significantly increased as heel height is increased[6-9]. The changes in joint angle result from the raised heel height cause alterations in lower extremity muscle activities. An increased activity of rectus femoris controls increased plantarflexion and knee flexion angle and increased activity of peroneus longus controls supination[7] have been reported.

Based on these observations, it is reasonable to assume that females with high-heeled shoes need to make more adjustments during walking. However, biomechanical changes generated by high-heeled shoes are not the only gait affecting factor in female population. When high-heeled shoes are worn, women often carry a load on one shoulder.

Asymmetrically carried load such as women’s purse would have its own biomechanical impact on joint kinematics and muscle activities in lower extremities. Asymmetrically carried load, unlike symmetrical load carriage such as backpack, shifts body’s centre of mass contralaterally and changes the pattern of trunk and lower extremity muscle activities. Despite the number of studies that have addressed the effect of high-heeled shoes, there are still no studies done to investigate the combined effect of foot wear and a load during walking.

Besides the findings of the above studies revealing the effect of either the high-heeled shoes or asymmetrical loading on lower extremity joint kinematics and muscle activities during gait in female population, the present study investigated the biomechanical effects while wearing different heights of high-heeled shoes and different weights of asymmetrical load owing to two needs. First, females with high-heeled shoes appear to be at higher risk of falling when compared with low-heeled shoes and it is expected to be higher when asymmetrical loading is added to body system, therefore, an understanding of posture alteration compensating both raised heel from footwear and laterally shifted centre of mass from asymmetrical loading is important. Second, in today’s society, many women wear high-heeled shoes in both professional and social settings, if stress caused from wearing high-heeled shoes and load carriage cannot be attenuated by changes in joint and muscles, it may be absorbed directly by the body and may increase the risk of developing musculoskeletal disorders. Thus, a thorough quantitative investigation of the gait is needed for the conditions with both shoes and load.

The purpose of the present study was to establish a basic understanding of the kinematic effects when walking in various heights of high-heeled shoes and weights of asymmetrical load. This knowledge will provide a basis for the recommendation of walking in high-heeled shoes while carrying load on one shoulder to minimize the biomechanical stress caused to muscles and joint in lower extremities.

METHODS

Participants

A total of fifteen female participants volunteered to participate in the study (mean ±SD age, 24.67 ±3.54 years; body weight, 54.96 ±6.67 kg; height, 162.2 ±3.91 cm). All of the participants had no previous musculoskeletal or neurologic injuries and were in good health. Participants were excluded from the study if they do not have a normal body mass index (range from 18.5 and 24.5). All participants had at least 3 years of experience wearing high-heeled shoes and wore them at least 3 times a week. From a questionnaire asking their experience of wearing high-heeled shoes, all participants perceived themselves as experienced high-heeled shoes wearer. The experimental protocol was approved by the university health sciences research ethics review board, and all participants gave written informed consent before data collection.

Shoes and Load Characteristics

All participants wore the same style of two pairs of high-heeled shoes and one pair of flat-heeled shoes. A pair of flat-heeled shoes of 1.1 cm sole was used as the control condition (Vans Inc., California, USA). Two high-heeled shoes were pin-pointed-heel stiletto shoes with heel height measured as 3.0 cm and 9.0 cm, respectively (Jones Apparel Group Inc., NY, USA). The base of the tip of stiletto heel was 0.9 cm^2. High-heeled shoes had leather upper part where as flat-heeled shoes had canvas upper parts. Three different sized shoes, 6, 7.5, and 9, were prepared to accommodate different foot sized participants.

A small nylon woman's purse sized 26.7 cm (L) x 3.8 cm (W) x 16.5 cm (H) was used to carry different weights on the subject's one shoulder (model: 7606 Lulu, Le Sportsac Inc., USA). Three different weights were used to create different loading conditions, no load, load of 5% of body mass, and 10% of body mass. Numerous load carriage studies have suggested that the 10% of body mass is the critical mass that alters the gait and balance and

Figure 1. Experimental shoes and purse

shows significant effect on participants when carried on one shoulder[10], therefore, 10% of BW was set as the maximum weight for present study. Circular shaped metal weights were placed into the purse and body of the bag was placed between the trunk and upper arm.

Experimental Protocol

Anthropometric data from each participant were measured to be used for the kinematic data analysis after participants were prepared with tight shorts and a shirt. Participants then performed a minimum of 5 walking trials for each condition. Total of 9 conditions created from 3 different heights of shoes and 3 different weights of load were tested in randomized order (Table 1). Participants were asked to walk across the testing area

Table 1.
Description of different conditions and number of trials performed.

Conditions	Shoes x Load	Number of Trials
#1	Flat-heeled shoes x 0 % BW	5
#2	Flat-heeled shoes x 5 % BW	5
#3	Flat-heeled shoes x 10 % BW	5
#4	3cm heeled-shoes x 0 % BW	5
#5	3cm heeled-shoes x 5 % BW	5
#6	3cm heeled-shoes x 10 % BW	5
#7	9cm heeled-shoes x 0 % BW	5
#8	9cm heeled-shoes x 5 % BW	5
#9	9cm heeled-shoes x 10 % BW	5

at their comfortable speeds. Participants were allowed to practice their walks in high-heeled shoes prior to the testing, and breaks were given between conditions to minimize muscle fatigue. At least eight steps were taken to be recorded within the 5 m distance to achieve high reliability[11]. A walking trial was deemed successful if participant walked without a fall and any displacement of load on the shoulder.

The walking path of approximately 8 m was surrounded by 9 infra-red, high-speed, optical cameras facing in from various angles to capture the motion. Walking movement was recorded at 200 Hz using a Vicon Motion Analysis System (Vicon MX-13, Oxford Metrics, Oxford, UK). It captured three-dimensional trajectories of 43 reflective markers placed on subject's full body. University of Ottawa Motion Analysis Model (UOMAM) marker set, a modified version of Plug-in-Gait model (VICON, Oxford Metrics, Oxford, UK) created by University of Ottawa, was adopted [23,24].

Data Processing and Analysis

Two consecutive strides for each right and left legs were analyzed for kinematics parameters, and all collected data were normalized to gait cycle for further analysis. Measurements of heel-strike and toe-off were obtained by visually inspecting the position of the virtual markers on the heel and toe. VICON Nexus software (v1.3) along with UOMAM market set was used to obtain lower-limb kinematic measurements of hip, knee, and ankle angles in sagittal and frontal planes. Computed joint angles data from Nexus were exported to Excel (Microsoft, Washington, USA) to find a maximum, minimum angle, and range of motion at each joint for each trial.

Initially, the data were examined and inspected. All the outliers, that are outside of two standard deviations of the variable mean, resulting from a measurement error such as hidden markers were excluded from the analysis as suggested from previous studies[12]. Data from five trials were then averaged for each condition for each participant. Descriptive statistics were performed for the temporospatial parameters and peak values of kinematic data using Statistical Package for Social Sciences (SPSS) version 16.0 software for Windows (SPSS Science, Chicago, Illinois). Firstly, independent *t*-tests were performed to find if there were significant differences in each dependent variable between the left (unloaded) and right (loaded) limb in each condition. To control type I errors when performing multiple independent t-tests, Bonferroni corrections were used by testing each comparison at a significant level of a/n, with n the number of comparisons. Secondly, peak joint angle and joint range of motion (ROM) were analyzed for both sides of the lower extremities during walking. A two-way repeated-measures ANOVA (three heel heights x three load weights) was employed to compare the data on each of dependent parameters. Tukey's post-hoc analysis was conducted if significant main effects or interactions were found. The level of 0.05 was used to test for significance.

RESULTS

All the subjects carried asymmetrical loads on right shoulder, therefore loaded limb indicates right limb in this paper. Temporospatial parameters showed no significant differences between the two limbs, thus, data from both limbs were combined for the calculation of mean and standard deviation and presented in Table 2. Mean and standard deviations of angle for hip, knee, and ankle are presented in Table 3, 4, and 5, respectively.

Loaded limb vs. unloaded limb

Hip joint demonstrated a significantly increased peak flexion angle on loaded limb during walking with a load for all shoes conditions. Both hip and knee peak abduction and adduction angle showed significant difference between the loaded and unloaded limb in loaded conditions (Table 3 and 4). Peak knee flexion and extension angle in loaded limb during walking with 10% BW carriage were significantly greater in flat-heeled shoes (p =

0.015, flexion; p = 0.010, extension) and 3 cm high-heeled (p = 0.018, flexion; p = 0.012, extension) conditions when compared with unloaded limb. Peak eversion angle demonstrated a significant difference between the two limbs in all conditions including unloaded walking (Table 5). The range of motion of hip, knee, and ankle did not show any significant differences between loaded and unloaded limbs. As hypothesized, for all lower extremity joints, significant differences were found between the loaded and unloaded limb most frequently during the walking with asymmetrical load of 10% BW and 9 cm high-heeled shoes combined.

Shoes Effect on Temporospatial and Kinematics of the loaded lower limb

The results from the study showed that high-heeled shoes have an influence on temporospatial parameters whether asymmetrical load was carried or not. Cadence decreased gradually with the increase in heel height during walking with no load; however, the change in cadence was not predictable once load was added. Stride time followed the same trend as the cadence. Stride length increased with the increase in heel height during walking with no load, but it decreased when a load of 10% BW was added. Double support time decreased with the increase in heel height in all loaded conditions (Table 2).

<u>Walking with no load</u> There were no significant changes in peak hip angles in sagittal plane during walking with no load. Peak hip abduction angle significantly decreased as heel height increased to 9 cm (p = 0.025, vs. flat-heeled; p = 0.000, vs. 3 cm high-heeled). Peak knee angles in sagittal plane showed a significant decrease with the increase in heel height to 9 cm, but the magnitude of the changes during walking without load carrying between different shoe conditions were smaller than the loaded conditions. Similar to the pattern displayed during 10% BW loaded walking, peak knee adduction angle increased gradually as heel height increased (p = 0.000 vs. flat-heeled). Peak knee abduction angle increased with both high-heeled shoes, but only 3 cm high-heeled shoes showed a significant difference (p =

0.034 vs. flat-heeled). In sagittal plane, peak ankle angles decreased with the increase in heel heights to 9cm and in frontal plane, it decreased during walking with 3 cm high-heeled shoes only (p = 0.002 vs. flat-heeled).

Walking with load Participants displayed a significantly reduced peak hip flexion angle when walked with high-heeled shoes of 3 cm or higher in 10% BW load conditions but not in 5% BW conditions (p = 0.001, 3 cm high-heeled vs. flat-heeled; p = 0.008, 9 cm high-heeled vs. flat-heeled). Peak hip abduction angle significantly decreased as participants walked with 9 cm high-heeled shoes during 10% BW loading, similar to unloaded walking, but no change was evident in 5% BW loading (p = 0.040, vs. flat-heeled; p = 0.000, vs. 3 cm high-heeled). Peak knee angles in sagittal plane significantly increased with the increase in heel height to 9 cm in both loading conditions. Also in frontal plane, it induced similar changes. Peak ankle angles in sagittal plane significantly decreased with the increase in heel height in both loading conditions. Peak ankle angles in frontal plane during both 5% and 10% BW loaded walking decreased only with 3cm high-heeled shoes.

*Loads Effect on T*emporospatial *and Kinematics of the loaded lower limb*

The results from the study showed that asymmetrically carried load has an influence on temporospatial parameters whether high-heeled shoes were worn or not. Cadence significantly decreased as load increases in flat-heeled shoes and 3 cm high-heeled conditions (p = 0.031; 0.044 respectively). When the subjects walked with flat-heeled shoes the stride length increased significantly as load increased to 5% BW (p = 0.043) or 10% BW (p = 0.013), but with high-heeled shoes it decreased significantly with increased load to 10% BW (p = 0.029, 3 cm high-heeled; 0.007, 9 cm high-heeled). Single support time showed an interesting trend. Single support time significantly increased when a load of 5% BW was carried for all shoes conditions (p = 0.002, 3 cm high-heeled; 0.017, 9 cm high-heeled shoes), although that of no heeled condition was not significant (p = 0.183). Step length also displayed a similar pattern as single support time.

Walking with flat-heeled shoes Peak hip flexion angle was significantly increased when participants walked with a load of 10% BW (p = 0.023 vs. flat-heeled, 0.004 vs. 5 cm high-heeled). Peak knee extension angle decreased when a load of 5% BW was added (p = 0.003 vs. no load) while it increased again as load increased to 10% BW (p = 0.033 vs. 5% BW). Peak ankle angles in sagittal and frontal plane did not show a significant difference with increased load weight during walking with flat-heeled shoes.

Walking with high-heeled shoes Peak hip angles in sagittal plane did not show a significant difference in all high-heeled conditions. Peak hip abduction angle increased only during walking with 5% BW load in 9 cm high-heeled shoes condition while it decreased only during walking with 5% BW load in 3 cm high-heeled shoes condition (p = 0014 vs. no load for 9 cm high-heeled, 0.005 vs. no load for 3 cm high-heeled). Peak knee flexion angle significantly decreased when 10% BW load was added during 9 cm high-heeled walking. Peak knee abduction angle increased when a load of 10% BW was added during 9 cm high-heeled gait (p= 0.004, 5% BW vs. no load; 0.040, 10% BW vs. no load). Peak ankle angles in sagittal and frontal plane did not show a significant difference with increased load weight during high-heeled walking. Although significant difference was not found, range of motion in frontal plane decreased while range of motion in sagittal plane increased with the increase in load weight. The effect of asymmetrical loading on the joint kinematics was more noticeable during 9 cm high-heeled walking than that of 3 cm high-heeled walking. The effect of asymmetrical loading was most prominent in proximal joints, hip and knee.

Table 2.
Mean and standard deviations for temporospatial parameters in each of walking condition (N = 15)

Parameters	Condition								
	Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Cadence (Steps/min)	125 ± 14.1	116.5 ± 18.7	119.4§ ± 10.4	118.8 ± 17.7	116.5 ± 25.1	114.3§ ± 15.1	116.5† ± 19.7	117.7 ± 14.5	117.7 ± 21.7
Stride Time (s)	0.96 ± 1.11	1.03 ± 0.92	1.00 ± 1.13	1.01 ± 2.07	1.03 ± 0.41	1.05 ± 2.48	1.03 ± 0.97	1.03 ± 0.79	1.02 ± 1.98
Stride Length (m)	1.48 ± 0.16	1.60§ ± 0.98	1.60§ ± 0.77	1.55 ± 0.71	1.63 ± 1.19	1.49§Ψ ± 0.54	1.56 ± 0.44	1.49† ± 0.18	1.45§Ψ† ± 0.10
Single Support Time (s)	0.43 ± 0.90	0.45 ± 0.15	0.44 ± 0.13	0.41 ± 0.77	0.43§ ± 0.44	0.42 ± 0.12	0.40 ± 0.09	0.43§ ± 0.07	0.39 Ψ ± 0.11
Double Support Time (s)	0.15 ± 0.87	0.14 ± 0.36	0.13 ± 0.11	0.19 ± 0.83	0.19 ± 0.88	0.21† ± 1.16	0.25†‡ ± 0.14	0.22†‡ ± 0.21	0.24†‡ ± 0.17
Step Length (m)	0.75 ± 0.08	0.77 ± 0.83	0.76 ± 1.02	0.75 ± 0.05	0.8 ± 0.12	0.72 ± 0.07	0.75 ± 0.07	0.74 ± 1.06	0.69§ ± 1.18

§ P < 0.05 vs. 0% BW
Ψ P < 0.05 vs. 5% BW
† P < 0.05 vs. Flat-heeled
‡ P < 0.05 vs. 3 cm High-heeled

Table 3.
Mean and standard deviation of maximum hip angle (degrees) on left and right limb in each of walking condition (N=15)

Angle	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Flexion	L	39.62 ± 5.11	38.76 ± 9.10	36.66 ± 4.09	37.27 ± 6.97	36.11 ± 4.19	34.9 ± 4.03	34.41 ± 9.74	38.37 ± 2.86	37.62 ± 3.84
	R	39.58 ± 4.33	37.51 ± 3.93	44.85§ Ψ ± 3.87*	38.97 ± 4.90	40.33 ± 5.11*	40.14 ± 7.94*	38.53 ± 3.77	38.74 ± 4.91*	40.48 ± 6.73*
Extension	L	-10.44 ± 1.02	-10.46 ± 1.88	-9.943 ± 2.97	-9.741 ± 1.47	-11.36 ± 2.46	-8.653 ± 2.67	-10.67 ± 2.13	-11.81 ± 2.60	-10.3 ± 2.99
	R	-9.15 ± 3.46	-8.597 ± 3.43	-10.752 ± 4.38	-7.61 ± 1.97	-8.256† ± 0.97	-8.973† ± 3.99	-8.389 ± 2.85	-8.873† ± 1.28*	-8.466† ± 3.10*
Adduction	L	17.66 ± 0.13	16.47 ± 1.63	18.19 ± 1.88	14.6 ± 6.34	14.53 ± 3.71	16.02 ± 3.62	16.96 ± 2.48	15.35 ± 2.22	15.65 ± 1.93
	R	19.7 ± 3.50*	18.76 ± 3.55*	20.66 ± 2.69*	18.58 ± 3.22*	16.98 ± 5.10*	16.57 ± 2.07*	20.76 ± 2.46*	15.83 ± 2.16*	16.74 ± 1.90*
Abduction	L	-3.842 ± 0.19	-4.202 ± 1.00	-2.581 ± 2.10	-3.099 ± 2.87	-3.431 ± 5.33	-1.882 ± 1.29	-4.384 ± 0.27	-5.71 ± 0.63	-2.29 ± 1.39
	R	-0.364 ± 5.10*	-0.45 ± 3.55*	-1.086 ± 3.97*	0.283 ± 6.21*	-0.739§ ± 0.88*	-0.166 Ψ ± 2.87*	-2.095†‡ ± 2.33*	-0.824§ ± 1.02*	-1.88†‡ Ψ ± 1.58*

§ P < 0.05 vs. 0% BW –Tukey post-hoc test
Ψ P < 0.05 vs. 5% BW –Tukey post-hoc test
† P < 0.05 vs. Flat-heeled –Tukey post-hoc test
‡ P < 0.05 vs. 3 cm High-heeled –Tukey post-hoc test
* P < 0.05 as comparing left with right limb – Independent t-test

Table 4.
Mean and standard deviation of maximum knee angle (degrees) on left and right limb in each of walking condition (N=15)

Angle	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Flexion	L	64.17 ± 9.33	66.34 ± 7.23	63.67 ± 11.06	60.73 ± 8.66	61.24 ± 6.79	61.68 ± 9.62	63.94 ± 8.15	66.68 ± 7.66	65.98 ± 6.09
	R	62.42 ± 10.22	60.562 ± 10.64	61.51 ± 9.23*	63.18 ± 9.79	62.12† ± 10.01	63.17† ± 7.24*	69.28†‡ ± 7.86	68.92†‡ ± 8.88	65.37†‡§ ± 9.87*
Extension	L	3.866 ± 2.46	1.13 ± 2.66	-1.061 ± 1.63	2.761 ± 2.01	0.5985 ± 0.33	-0.76 ± 0.97	-0.674 ± 1.03	-0.384 ± 0.88	0.824 ± 0.021
	R	4.292 ± 1.97	1.713§ ± 1.76	4.70Ψ ± 2.33*	3.334 ± 0.091	3.43 ± 0.17*	2.501 ± 0.24*	0.322†‡ ± 0.088	-0.715†‡ ± 0.36	-0.565†‡ ± 0.47
Adduction	L	0.874 ± 0.086	2.316 ± 0.63	4.323 ± 0.87	2.99 ± 1.11	4.044 ± 1.62	4.153 ± 0.84	4.338 ± 1.03	4.237 ± 0.90	2.718 ± 0.28
	R	4.08 ± 0.48	5.72 ± 0.64	4.279 ± 0.97	5.512 ± 1.02	5.721 ± 1.37	5.205 ± 1.63	7.415 ± 1.97*	7.083 ± 2.11*	7.503 ± 1.03*
Abduction	L	-10.2 ± 3.16	-10 ± 4.33	-9.38 ± 3.97	-10.3 ± 6.02	-10.4 ± 4.97	-9.12 ± 4.21	-10.4 ± 5.11	-9.65 ± 6.39	-9.49 ± 3.77
	R	-10 ± 5.76	-9.37 ± 5.55	-9.9 ± 5.22	-8.49† ± 6.33	-9.12 ± 6.85	-9.62 ± 6.79	-9.18 ± 4.63*	-8.34†‡ ± 2.89*	-8.42†‡ ± 4.21*

§	$P < 0.05$ vs. 0% BW –Tukey post-hoc test
Ψ	$P < 0.05$ vs. 5% BW –Tukey post-hoc test
†	$P < 0.05$ vs. Flat-heeled –Tukey post-hoc test
‡	$P < 0.05$ vs. 3 cm High-heeled –Tukey post-hoc test
*	$P < 0.05$ as comparing left with right limb – Independent t-test

Table 5.
Mean and standard deviation of maximum ankle angle (degrees) on left and right limb in each of walking condition (N=15)

Angle	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Dorsi- flexion	L	14.13 ± 6.04	12.86 ± 6.12	12.33 ± 4.12	0.948 ± 5.33	2.467 ± 5.97	1.08 ± 2.10	-11.42 ± 4.15	-9.021 ± 4.13	-10.37 ± 5.32
	R	9.65 ± 5.13	10.69 ± 6.78	12.06 ± 2.77	3.203† ± 3.97	1.5 ± 3.49	1.63 ± 3.19	-9.91†‡ ± 3.46	-8.522† ± 6.79	-9.087†‡ ± 4.35
Plantar-flexion	L	-29.26 ± 5.97	-32.77 ± 5.22	-22.53 ± 5.19	-32.49 ± 6.27	-33.66 ± 6.99	-33.97 ± 1.25	-38.81 ± 5.11	-40.64 ± 8.99	-39.41 ± 6.21
	R	-26.13 ± 6.66	-23.48 ± 4.19	-24.16 ± 5.40	-27.82† ± 7.21	-33.13 ± 5.74	-31.18 ± 2.69	-38.76†‡ ± 4.19	-36.85†‡ ± 8.20	-39.11†‡ ± 4.22
Inversion	L	15.07 ± 5.10	17.08 ± 2.88	12.61a^2 ± 2.67	12.29 ± 3.45	12.98 ± 6.19	12.12 b^1 ± 5.77	17.24b^2 ± 4.16	14.99 ± 1.16	15.2 ± 2.58
	R	9.37 ± 2.64*	9.599 ± 6.11*	8.482 ± 4.97*	1.770† ± 3.21*	3.784† ± 7.20*	3.216† ± 4.37*	6.222‡ ± 1.46*	6.482‡ ± 5.22*	8.315‡ ± 6.11*
Eversion	L	-4.972 ± 6.28	-3.611 ± 2.16	-3.812 ± 2.66	-0.536 ± 3.14	-0.992 ± 2.54	-0.586 ± 4.17	2.821 ± 8.21	2.08 ± 2.13	2.417 ± 3.64
	R	-1.915 ± 0.83	-1.639 ± 6.33	-1.619 ± 3.22	-2.519† ± 1.36	-3.389† ± 3.26	-2.821† ± 2.65	-0.998‡ ± 2.97	-1.730‡ ± 3.19	-2.163‡ ± 5.21

§ P < 0.05 vs. 0% BW –Tukey post-hoc test
Ψ P < 0.05 vs. 5% BW –Tukey post-hoc test
† P < 0.05 vs. Flat-heeled –Tukey post-hoc test
‡ P < 0.05 vs. 3 cm High-heeled –Tukey post-hoc test
* P < 0.05 as comparing left with right limb – Independent t-test

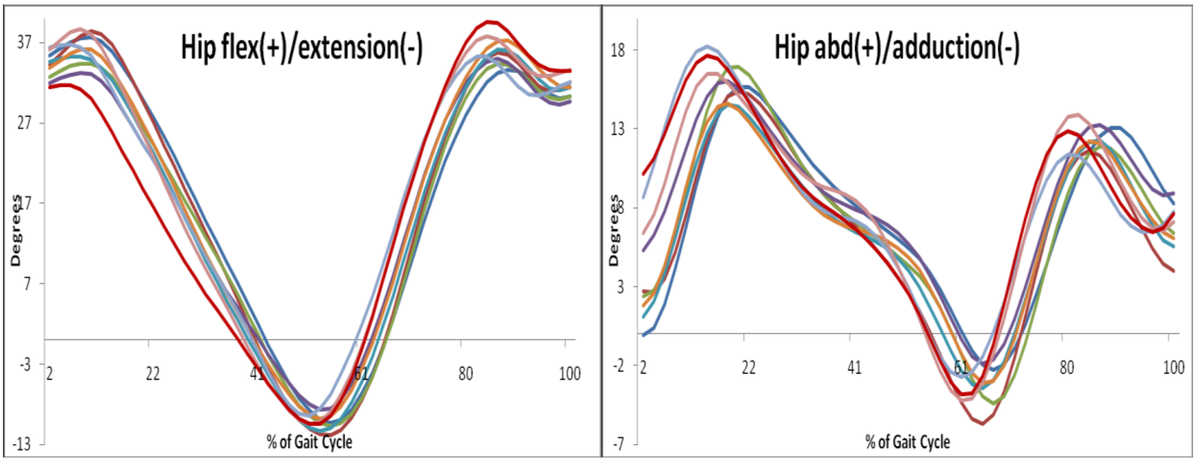

Figure 2. Hip joint angles in sagittal and frontal planes during walking with 9 cm, 3 cm high-heeled shoes and flat-heeled shoes and asymmetrical load carriage (N = 15).

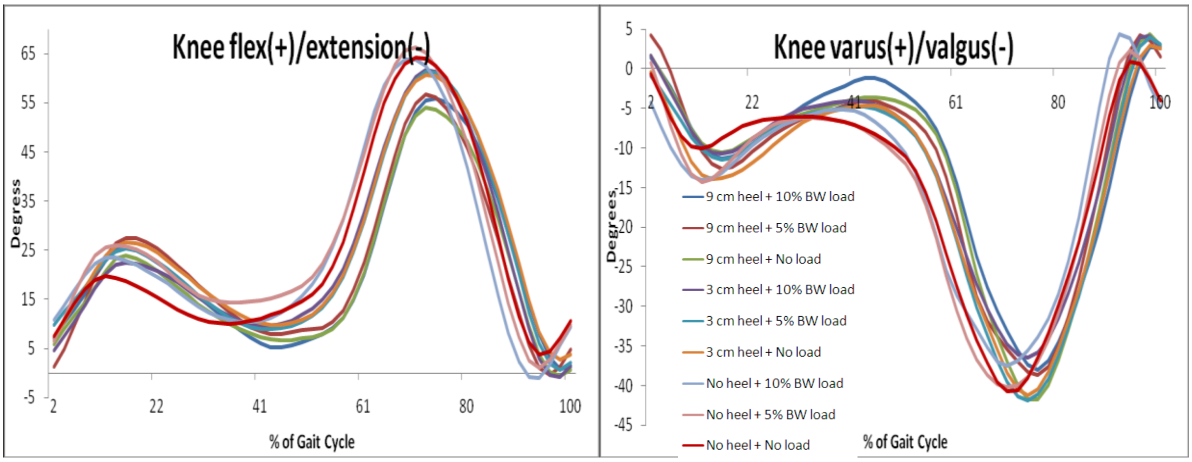

Figure 3. Knee joint angles in sagittal and frontal planes during walking with 9 cm, 3 cm high-heeled shoes and flat-heeled shoes and asymmetrical load carriage (N = 15).

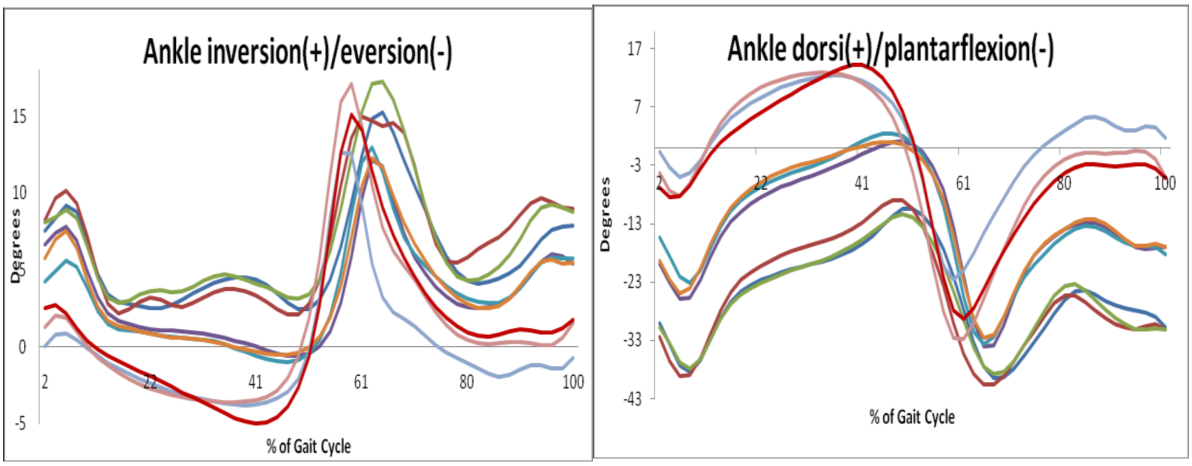

Figure 4. Ankle joint angles in sagittal and frontal planes during walking with 9 cm, 3 cm high-heeled shoes and flat-heeled shoes and asymmetrical load carriage (N = 15).

DISCUSSION

Previous studies have investigated load carriage or high-heeled shoes influences on gait separately. The main objective of this study was to evaluate the kinematic changes in lower extremity during walking in various heights of high-heeled shoes and carrying different weights of asymmetrical load in young healthy high-heeled shoes wearers.

Loaded limb vs. unloaded limb

Temporospatial parameters showed no significant difference between loaded and unloaded limbs. This agrees with the study done by DeVita et al.,[12] which reported no change in the right to left stride ratio during side loaded walking, an asymmetrical load of 10% BW is not heavy enough to significantly alter temporospatial parameters between the loaded and unloaded limb within a subject. However, lower extremity joint angles in sagittal and frontal planes showed remarkable differences between the two limbs. Carrying a load of 10% BW significantly affected hip flexion angles and knee flexion and extension angles regardless of heel height. The difference appearing between the limbs rooted from the significant elevation of strap supporting shoulder with concomitant lateral bending of the spine away from the weight of the load[13]. The results of present study showed that the heel height influenced the frontal plane movements more than the movements in other planes at knee joint. Walking with 9 cm high-heeled shoes exhibited significant differences in the knee abduction and adduction angles regardless of load carriage. One of the interesting findings from the present study is the frontal plane movement between the two limbs. Knee and ankle peak angles in frontal plane showed a significant difference between the loaded and unloaded limb in all nine testing conditions that including flat-heeled and no load conditions. The significant difference found in all conditions including control condition indicates that the participants may not display congruence between left and right limb in terms of generating joint angle. An example supports this notion is the occurrence of unilateral osteoarthritis (OA) developed by elder population. According to the USA National Health and Nutrition Examination Survey from 1997[14], 50% of OA participants show its symptoms unilaterally. Despite the large number of patients suffering from the unilaterally occurring musculoskeletal disorders, many of the kinematics studies on knee and ankle paid little attention on the comparison of frontal plane movement between the two limbs within the participants.

Shoes Effect on Temporospatial and Kinematics of the loaded lower limb

High-heeled shoes alter gait characteristics whether a load was carried or not. Eisenhardt et al.[15] have looked at the effect of high-heeled shoes during level walking on temporospatial parameters in females and reported a decrease in cadence and stance duration and increase in double support time. During walking with no load, participants from the present study also demonstrated a decrease in cadence and increase in double support time with the increase in heel height. During walking with a load, double support time increased significantly and its magnitude was greater when a load of 10% BW was carried. The double support time was increased to gain balance because the added load on one side caused body to stay in both feet on the ground longer to obtain a firm balance to take the next step. Stride length increased with heel height during unloaded conditions but during loaded conditions stride length decreased. Participants with loads took shorter steps with high-heeled shoes. The interaction of high-heeled shoes and asymmetrical load carriage was observable as influence of heel height on stride length depends on the load carriage.

High-heeled shoes alter three-dimensional kinematics on lower extremities during locomotion. As previously reported, significant increase in ankle plantarflexion angle during walking with high-heeled shoes was evidenced in the present study (Figure 3). Particularly, peak ankle plantarflexion angle demonstrated an increase with the raised heel height regardless the load weight. Ebbelling et al.[6] and Stefanyshyn et al.[7] also reported similar findings from their studies with various heights of high-heeled shoes. Although ankle angle in sagittal plane demonstrated an increase regardless of the load weight, when a load of 10% BW was carried the magnitude of change in angle was at its greatest. In addition to the raised heel height, an increase in load weight also contributed to increase plantarflexion angle further during walking by shift the position of centre of gravity away from the midline and toward the load.

Kinematic changes in lower extremities in high-heeled gait are mainly caused by the large increase in plantarflexion angle. Raised heel over 9 cm caused the centre of mass to shift anteriorly in habitual high-heeled shoes wearers[4], compensational changes in joint angles in lower extremities were needed to keep the balance during walking. As a consequence, hip and knee joints in the sagittal plane were altered to compromise any changes occurred at ankle. High-heeled shoes of 9 cm significantly decreased peak knee and hip flexion angles, and changes in these angles were greater when a load 0f 10% BW was carried. During walking, an added load exacerbated the joint angle changes caused by the raised heel height. Ucanok and Peterson[16] reported a gradual increase in knee flexion angle with the raised heel height. The present study confirmed the previous findings in all loading conditions, however, during the 10% BW loaded gait, the peak knee flexion angle was larger than that of during 5% BW loading conditions. Load and high-heeled shoes together increased knee flexion angle further during walking.

Ankle and knee range of motion in the sagittal plane decreased with the increase in heel height. A significantly increased plantarflexion due to the raised heel affected the knee joints mostly, thus, at the knee level most of the compensational work has done. Participants demonstrated no changes in hip range of motion with the increase in heel height.

Loads Effect on Temporospatial and Kinematics of the loaded lower limb

Previous studies suggested temporospatial parameters to be used to indicate balance and stability during gait[17]. Less stable gait is characterized by an increase in stride length and double support time and decrease in cadence and single support time. From the results, cadence decreased and stride length increased with the added load when participants walked with flat-heeled shoes. Taken together, these changes indicated that participants when walking with an asymmetrical load adopted changes in temporospatial parameters to achieve a more balanced gait. This agrees with the Hong & Li[18]'s study of 12 years old children reported in that an asymmetrically carried load higher than 10% BW alters gait temporospatial parameters. However, during high-heeled walking, the changed pattern in temporospatial parameters was not congruent with Hong & Li in two ways. First, when participants wore high-heeled shoes there was no gradual increase or decrease with the increase in load weights. Second, stride length decreased with the increase in load weight during high-heeled gait. When compared with flat-heeled gait, participants demonstrated more stable gait pattern during 5 cm high-heeled shoes than flat-heeled shoes and less stable gait pattern during 9 cm high-heeled shoes. This may be due to the adaptation mechanism that participants have built through many years of wearing high-heeled shoes.

The pattern seen in the changes in the lower extremity joint angle during flat-heeled shoes gait was consistent with general observations previously reported[19, 20]. Although previous studies achieved data from a symmetrical loading, a lesser hip flexion and extension during initial weight-bearing phase with a lesser knee flexion and extension were in agreement with current study. The asymmetrically carried load on one shoulder affected the trunk kinematics in female participants during walking[17], the compensational alterations to counter balance the trunk are done at its nearby joint, pelvis level. This is confirmed by the present result that shows an absence of significant difference in ankle angles between different loading conditions regardless of heel height.

Carter et al.[21] studied a relationship between frontal plane ankle range of motion and frontal plane control that determined from step width variability and concluded that the increased frontal plane ankle range of motion is associated with improved frontal plane control during gait. From our result, female participants showed a decrease in frontal plane ankle range of motion with increase in load weight. This suggests that when 9 cm high-heeled shoes are worn, asymmetrically carried load challenges frontal plane movement and may promote a loss of balance.

It is acknowledged that the study has certain limitations. Given the limited study sample and the wide range of testing conditions, the statistical power of the study might not have been sufficient to generalize the findings. However, several hypothesized results pertaining to the elevated heel and the asymmetrical load carriage were confirmed and presented moderate to large effect sizes. In addition, some of the associations uncovered may have occurred by chance, but it is likely that the comparisons with moderate and large effect size reflect the true effects of independent variables.

CONCLUSION

The findings of this study suggested that the increased shoe heel height and asymmetrically carried load weight caused alterations in temporospatial parameters and lower extremity joint kinematics during walking. Increased double support time and stride length and decreased cadence during high-heeled walking with load carriage indicated that participants demonstrated a more conservative walking pattern. Increased plantarflexion during high-heeled walking caused knee and hip to alter kinematics to compensate for changes at the ankle. When load was added to high-heeled gait, increase in knee flexion angle was further exacerbated. The combined effect of high-heeled shoes and load carriage together altered lower extremity joint kinematics further. The changes in hip angle were mostly caused by the asymmetrical loading while changes in ankle angle were mostly caused by the raised heel height.

Walking in high-heeled shoes forces the person to adjust the posture with increase knee flexion which may accelerate knee pain or musculoskeletal disorders. An asymmetrical load only serves to further exacerbate the joints in lower extremity during high-heeled walking. The use of both high-heeled shoes and asymmetrical load carriage together is very popular among women. The findings from this study recommend the users to avoid carrying heavy load in purses when high-heeled shoes are worn.

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Article 2

EFFECTS OF ASYMMETRICAL LOAD CARRIAGE AND HIGH-HEELED SHOES ON LOWER EXTREMITY JOINT KINETICS IN HEALTHY YOUNG WOMEN DURING WALKING

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Abstract

A within-subject comparative study of walking while wearing different heights of high-heeled shoes and carrying different weights of asymmetrical load carriage was performed to examine any changes in lower extremity joint kinetics associated with the combined effect of shoes and load during level ground walking. A volunteer sample of 15 healthy young female habitual high-heeled shoes wearers participated in the study. Joint force and moment of hip, knee, and ankle on both loaded and unloaded limbs during walking were studied. High-heeled shoes and asymmetrically carried load together altered joint kinetics during gait. Hip extensor moment significantly increased with heel height increase but not with load weight increase. Knee extensor moment was affected by both high-heeled shoes and load carriage. Ankle plantarflexor moment decreased with high-heeled shoes but increased with load weight. As a result of high-heeled shoes and load carriage, knee extensor moment increased and ankle plantrarflexor moment diminished. In conclusion, the present study suggests that when high-heeled shoes and asymmetrically carried load are combined, the alterations made at each joint are much greater than that of high-heeled shoes or load carriage alone would cause.

INTRODUCTION

A load carriage is widely performed in our daily lives. Concerns have been raised over recent decades about pains corresponding to load carriage[1]. Research findings on the relationship between load carriage and temporal, kinetic, and kinematic characteristics of gait revealed that significant changes in body posture and gait pattern were evident while carrying a heavy load compared with light load indicating that the risk of encountering stress-related injuries is considerably greater as the load increased in magnitude[2]. From a biomechanical point on the effect of carrying load, the load carriage hinders physical performance[3], causes loss of pelvic and thoracic rotation[4], increases joint angles in lower extremities[5], increases centre of mass excursion[3] and increases vertical ground reaction force (GRF)[6]. From a physiological point, the load carriage increases metabolic cost significantly with increased magnitude[7]. A prolonged ambulation with load in altered posture may lead to musculoskeletal problems and fatigue.

Most of the research about the effect of carrying bags in adults focuses on use of backpacks for recreation or heavy load carriage in military personnel. In these studies, different load weights were often compared to find a threshold point or optimum weight to be put into the backpack while minimize biomechanical stresses to carrier’s musculoskeletal structure. Studies in backpack carrying found significant biomechanical changes made to posture and gait patterns. Results from these studies showed significantly increased ground reaction force as a load in backpacks increased[8]. However, in general female population, backpack carriage is not the most popular load carrying methods. Other carrying method such as asymmetrical load carrying method is implemented by women. Thus, it is not reasonable to apply such conclusions from backpack previous researches directly to asymmetrical load carrying in woman. Furthermore, when footwear changes from low-heeled normal walking shoes to high-heeled shoes the body must compensate any changes caused by load and shoes.

Increased complaints about back and shoulder pain from carrying load are evident as it is required to carry load in our daily lives[6]. Also, increased complaints about back and foot pain and increased incidents of falls and discomfort from wearing high-heeled shoes are evident among women[9]. Both asymmetrical load carriage and high-heeled shoes are frequently encountered during walking and in turn, problems have raised concerns among women. However, so far information about examining the effect of footwear along with loading is lacking. Therefore, the purpose of the current study was to examine the combined effects of asymmetrical load carriage on lower extremities joint kinetics during walking wearing different types of high-heeled shoes in young healthy habitual high-heeled shoes wearers. This study will provide important information on the magnitude of external loading imposed on human body while carrying loads during walking and would add the understanding to gait and posture adaptation to the combined two conditions.

METHODS

Participants

A total of fifteen female subjects volunteered to participate in the study (mean ± SD age, 24.67 ± 3.54 years; body weight, 54.96 ± 6.67 kg; height, 162.2 ±3.91 cm). All of the participants had no previous musculoskeletal or neurologic injuries and were in good health conditions. Subjects were excluded from the study if they do not have a normal body mass index (range from 18.5 and 24.5). The experimental protocol was approved by the university health sciences research ethics review board, and all subjects gave written informed consent before the data collection.

Data Collection

Kinematics and kinetics data were collected and analyzed using a Vicon Motion Analysis System (Vicon MX-13, Oxford Metrics, Oxford, UK) with nine infrared cameras recording three dimensional motion at 200 Hz, coupled with three force plates (models 9286AA, Kistler Instruments Corp, Winterhur, Swtz; FP 4060-08, Bertec Corporation, Columbus, OH, USA) recording ground reaction force at 1000 Hz. The force plates were embedded on the ground in the middle of walkway in such a way that participants could plant their foot on each plate consecutively. Forty-three 14 mm reflective markers identifying body segments, according to the University of Ottawa Motion Analysis Model (UOMAM) marker set[28, 29], were attached to the participant to capture walking motion. Participants were asked to wear black tight shorts and a shirt to prevent unnecessary marker movements due to the loose clothing. Anthropometric measures, body weight and height, leg length, and ankle and knee width, were taken.

Participants walked with and without asymmetrical load and high-heeled shoes. Three different weights of asymmetrical load, 0%, 5%, and 10% of body mass, were tested during normal walking with flat shoes and high-heeled walking with 3 cm and 9 cm stiletto shoes. Metal

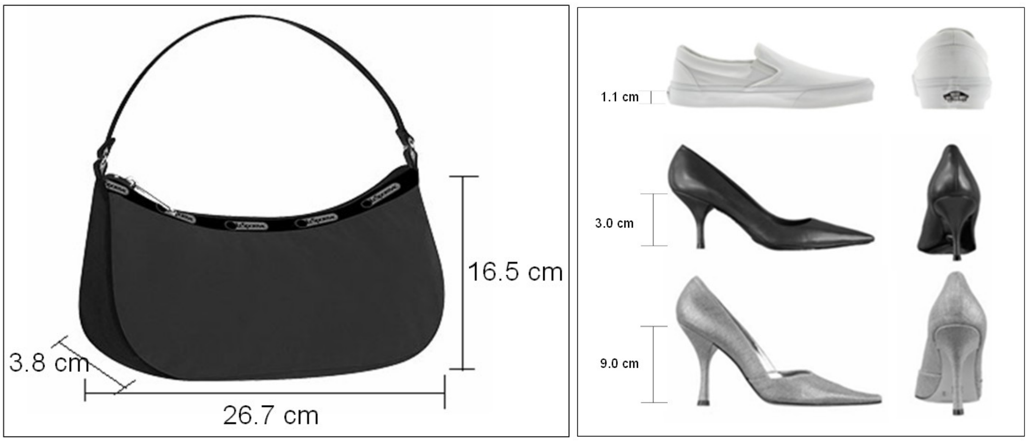

Figure 1. Experimental shoes and purse

weights were used to build 5% and 10% of body mass and were put into a woman's one strap nylon shoulder purse measured as 26.7 cm (L) x 3.8 cm (W) x 16.5 cm (H) (model: 7606 Lulu, Le Sportsac Inc.). One pair of flat shoes with 1.1 cm heel height (Vans Inc., California, USA) and two pairs of stiletto high-heeled shoes (Jones Apparel Group Inc., NY, USA) were used.

Participants walked across the testing area of approximately 8 m in her comfortable speed under nine different conditions. For each of the conditions, five successive trials were collected in randomized order then averaged for further analysis. The trial was considered good when participants walked naturally while step on two force plates consecutively without a fall or displacement of load from her shoulder. Participants were allowed to practice walks with high-heeled shoes if necessary, and breaks were given between the trials to prevent fatigues.

Data Analysis

A special attention was paid to make sure that one stride began with a heel contact on the third or fourth step of walking and ended with subsequent heel contact of same foot, this was to collect kinetic data when subject is in uniform motion. One full gait cycle per each foot was analyzed. Gait events were identified using visual observation of the motion and force data. VICON Nexus software (v1.3) along with UOMAM marker set was used to obtain lower-limb kinetic measurements of hip, knee, and ankle angles in all three planes. Computed joint angles then employed to calculate joint force and moment using inverse dynamics using linear and angular Newtonian equations of motion and methods[10]. The data was normalized to a stride period of 100% by using Polygon software (VICON, Oxford, UK). All data were normalized by body weight and presented as 100% of gait cycle.

Two sets of statistical test were performed in the present study. Firstly, the dependent variables, peak moments in three planes, were compared using two-way repeated measures of

ANOVA (three heel heights x three load weights) at a 95% confidence level. If any difference was found between the independent variables, Tukey's post hoc test was performed for further detection. Effect of shoes and asymmetrical load as well as the interaction between the independent variables were found from the statistical tastings. Secondly, paired sample *t*-tests were implemented for all dependent parameters to find a significant difference between loaded and unloaded limb.

RESULTS

All participants carried an asymmetrical load on their right shoulders, therefore loaded limb indicates right limb in this paper. Mean and standard deviations of peak moment for hip, knee, and ankle in all three planes are presented in Table 1 to 3, respectively.

Loaded limb vs. unloaded limb

No significant difference was found between loaded and unloaded limb in lower extremity joint kinetics during walking with no load. Interestingly, significant differences in joint kinetics between the two limbs are found only during high-heeled gait with load. During both heights of high-heeled walking with a load of 5% BW or heavier, loaded limb demonstrated a lower ankle adductor moment than unloaded limb (3 cm high-heeled: p = 0.022, 0.035; 9 cm high-heeled: 0.021, 0.029).

Shoes Effect on Kinetics of the loaded lower limb

<u>Walking with no load</u> During walking with no load, no change in peak hip flexor moment was found but there was an increase in peak hip extensor moment with high-heeled shoes (p = 0.005, flat-heeled vs. 3 cm high-heeled; p = 0.002, flat-heeled vs. 9 cm high-heeled). High-heeled shoes, regardless of heel height, increased peak hip extensor moment (p = 0.036, flat-heeled vs. 3 cm high-heeled; p = 0.028, flat-heeled vs. 9 cm high-heeled). A larger peak knee extensor moment was also found with the increase in heel height (p = 0.033,

flat-heeled vs. 3 cm high-heeled; p = 0.008, flat-heeled vs. 9 cm high-heeled; p = 0.036, 3 cm high-heeled vs. 9 cm high-heeled). A larger peak varus moment was found between 3 cm high-heeled shoes and 9 cm high-heeled shoes (p = 0.001). Peak ankle plantarflexor moment was reduced with 9 cm high-heeled shoes in both loading conditions (p = 0.000, flat-heeled vs. 9 cm high-heeled; p = 0.001, 3 cm high-heeled vs. 9 cm high-heeled). Peak eversion moment decreased with the increase in heel height (p = 0.000, flat-heeled vs. 9 cm high-heeled; p = 0.001, flat-heeled vs. 9 cm high-heeled; p = 0.003, 3 cm high-heeled vs. 9 cm high-heeled).

<u>Walking with load</u> Walking in flat-heeled shoes and carrying a load did not cause any significant changes in peak hip flexor moment, but both high-heeled shoes increased peak hip extensor moment in both 5% and 10% BW loading conditions. Peak hip extensor moment showed the same pattern. A larger extensor moment was found with high-heeled shoes when a load of 10% was carried (p = 0.002, flat-heeled vs. 9 cm high-heeled).

Also a larger knee varus moment was found with the increase in heel height in both loaded conditions. Peak ankle plantarflexor moment during walking was reduced with 9 cm high-heeled shoes in both loading conditions. Peak eversion moment decreased with the increase in heel height in both loading conditions. During unloaded gait, eversion moment decreased gradually as heel height of shoes, but during loaded gait with a load of both 5% and 10% BW, there was no difference between 3 cm high-heeled and 9 cm high-heeled shoes conditions.

Loads Effect on Kinetics of the loaded lower limb

<u>Walking with flat-heeled shoes</u> Asymmetrically carried load significantly increased peak hip flexor moment during all loading conditions, peak knee extensor moment during 5% BW loading condition, and peak plantarflexor moment during 10% BW loading condition. The p values from the comparisons were 0.003, no load vs. 5% BW; 0.006, no load vs. 10%

BW; 0.021, 5% BW vs. 10% BW, respectively for peak hip flexor moment, 0.000, no load vs. 5% BW, respectively for peak knee extensor moment, and 0.002, no load vs. 5% BW; 0.008, no load vs. 10% BW; 0.001, 5% BW vs. 10% BW, respectively for peak plantarflexor moment.

<u>Walking with high-heeled shoes</u> Peak hip flexor moment increased with the increase in load weight similar to flat-heeled shoes condition in 3 cm high-heeled gait, however, it decreased with the increase in load weight in 9 cm high-heeled gait (for 3 cm high-heeled: p = 0.002, No load vs. 10% BW; for 9 cm high-heeled: p = 0.018, No load vs. 10% BW). Peak hip abductor moment decreased with increase in load weight during both high-heeled walking (for 3 cm high-heeled: p = 0.010, No load vs. 5% BW; 0.022, No load vs. 10% BW; for 9 cm high-heeled: p = 0.022, No load vs. 10% BW; 0.027, 5% BW vs. 10% BW). Peak knee extensor moment increased as load weight increased to 10% BW in both high-heeled conditions (for 3 cm high-heeled: p = 0.005, 5% BW vs. 10% BW; for 9 cm high-heeled, 0.003, 5% BW vs. 10% BW). Peak valgus moment increase when load was carried only during 9 cm high-heeled walking (p = 0.016, No load vs. 5% BW, 0.020, No load vs. 10% BW). Peak plantarflexor moment of the ankle joint increased when participants carried a load of 10% in all high-heeled shoes conditions (for 3 cm high-heeled: p = 0.012, No load vs. 10% BW; for 9 cm high-heeled, p = 0.019, No load vs. 10% BW). Peak dorsiflexor moment showed a similar trend as well (for 3 cm high-heeled: p = 0.010, No load vs. 10% BW; for 9 cm high-heeled, 0.005, No load vs. 10% BW).

Table 1.
Mean and standard deviation of maximum and minimum hip moment (N·m/kg) on left and right limb (N=15)

Moment	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Sagittal Max.[a]	L	0.921 ± 1.33	0.903 ± 1.25	1.001 ± 1.00	0.928 ± 1.20	1.001 ± 0.99	0.965 ± 1.88	0.785 ± 1.22	0.984 ± 1.99	1.124 ± 1.35
	R	0.886 ± 0.89	0.943 ± 1.22	1.064Ψ ± 1.09	0.719 ± 0.97	0.839 ± 0.25	0.925Ψ ± 1.39	1.118 ± 1.33	1.068 ± 2.55	0.814Ψ ± 1.99
Sagittal Min.[b]	L	-0.452 ± 0.36	-0.531 ± 0.36	-0.674 ± 0.55	-1.004 ± 0.14	-1.559 ± 0.12	-0.788 ± 0.22	-1.006 ± 0.21	-1.028 ± 1.25	-1.201 ± 0.77
	R	-0.471 ± 0.15	-0.551 ± 0.53	-0.459 ± 0.33	-1.340† ± 1.22	-1.089† ± 0.22	-1.116† ± 0.45	-0.943† ± 0.11	-1.159† ± 0.48	-1.271† ± 0.94
Frontal Max. [c]	L	0.298 ± 0.66	0.600 ± 0.22	0.294 ± 0.88	0.337 ± 0.22	0.280 ± 0.55	0.240 ±0.63	0.622 ± 0.77	0.404 ± 0.57	0.386 ± 0.75
	R	0.298 ± 0.34	0.515 ± 0.87	0.340 ± 0.84	0.343 ± 0.36	0.285 ± 0.36	0.224 ± 0.37	0.403 ± 0.64	0.339 ± 0.34	0.383 ± 0.96
Frontal Min. [d]	L	-0.874 ± 0.28	-0.613 ± 0.34	-1.086 ± 0.53	-0.9433 ± 0.33	-1.016 ± 0.75	-0.994 ± 0.15	-0.928 ± 0.35	-1.133 ± 1.04	-0.998 ± 0.85
	R	-1.058 ± 1.55	-0.746 ± 0.99	-1.005 ± 1.03	-1.524 ± 0.64	-0.991Ψ ± 0.82	-1.148Ψ ± 0.49	-1.108 ± 1.01	-1.245† ± 0.55	-1.097Ψ§ ± 0.88
Transverse Max. [e]	L	0.115 ± 1.66	0.243 ± 0.15	0.211 ± 0.97	0.243 ± 0.96	0.308 ± 0.33	0.367 ± 0.97	0.312 ± 0.36	0.450 ± 0.57	0.419 ± 0.43
	R	0.140 ± 0.39	0.257 ±0.33	0.149 ± 0.85	0.360† ± 0.25	0.241 ± 0.94	0.273 ± 1.25	0.389† ± 1.67	0.351 ± 0.36	0.387† ± 0.57
Transverse Min. [r]	L	-0.153 ± 0.24	-0.118 ± 0.86	-0.145 ± 0.76	-0.211 ± 0.11	-0.123 ± 0.68	-0.163 ± 0.25	-0.067 ± 0.15	-0.097 ± 0.23	-0.093 ± 0.37
	R	-0.139 ± 0.55	-0.153 ± 0.44	-0.115 ± 0.16	-0.133 ± 0.19	-0.137 ± 0.27	-0.188 ±0.66	-0.071†‡ ± 0.13	-0.096†‡ ± 0.28	-0.019†‡ ± 0.11

Table 2.
Mean and standard deviation of maximum and minimum knee moment (N·m/kg) on left and right limb (N=15)

Moment	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Sagittal Max.[a]	L	0.240 ± 1.55	0.327 ± 0.96	0.200 ± 2.22	0.452 ± 1.02	0.697 ± 1.00	0.384 ± 1.33	0.449 ± 0.63	0.312 ± 0.19	0.549 ± 0.12
	R	0.212 ± 0.66	0.302 ± 0.45	0.234 ± 1.85	0.471 ± 1.33	0.249 ± 0.12	0.496 ± 0.32	0.419 ± 0.85	0.403 ± 0.24	0.358 ± 1.25
Sagittal Min.[b]	L	-0.437 ± 0.37	-1.385 ± 0.46	-0.580 ± 0.57	-0.505 ± 0.98	-0.741 ± 0.32	-1.190 ± 0.48	-0.775 ± 1.73	-1.041 ± 1.88	-1.027 ± 1.34
	R	-0.886 ± 0.64	-1.385 Ψ ± 0.42	-0.904 ± 0.54	-1.084† ± 0.14	-0.889 ± 0.22	-1.036§ ± 1.54	-1.456†‡ ± 1.29	-1.279 ± 1.37	-1.402†§ ± 0.54
Frontal Max.[c]	L	0.195 ± 3.86	-0.285 ± 0.82	0.135 ± 1.98	0.076 ± 2.22	0.219 ± 1.24	0.0609 ± 0.41	0.144 ± 0.38	0.242 ± 1.26	0.0959 ± 0.45
	R	0.123 ± 0.74	-0.733 ± 2.64	0.127 ± 2.77	0.0719 ± 0.39	0.060 ± 0.45	0.0407 ± 0.27	0.133‡ ± 0.63	0.216†‡Ψ ± 0.38	0.194†‡Ψ ± 0.24
Frontal Min.[d]	L	-0.846 ± 0.33	0.0718 ± 0.55	-0.724 ± 1.02	-0.666 ± 0.33	-0.810 ± 1.54	-0.882 ± 1.25	-0.786 ± 0.56	-1.036 ± 0.95	-0.095 ± 0.55
	R	-0.587 ± 1.42	0.0596 ± 0.73	-0.377 ± 0.99	-0.606 ± 1.22	-0.412† ± 0.94	-0.501 ± 0.38	-0.491 ± 0.77	-0.613†Ψ ± 0.85	-0.527Ψ ± 1.21
Transverse Max.[e]	L	0.0329 ± 0.11	-0.115 ± 0.18	0.0529 ± 0.77	0.0745 ± 1.63	0.0625 ± 0.12	0.0465 ± 0.95	0.0643 ± 0.35	0.0397 ± 0.42	0.130 ± 0.54
	R	0.0450 ± 0.16	-0.151 ± 2.47	0.0079 ± 1.85	0.0228† ± 0.12	0.0310† ± 0.22	0.0202† ± 0.12	0.0145†‡ ± 0.83	0.0629†‡ ± 0.44	0.029† ± 0.55*
Transverse Min.[r]	L	-0.135 ± 2.52	-0.114 ± 0.88	-0.196 ± 1.25	-0.269 ± 0.66	-0.197 ± 0.96	-0.240 ± 0.82	-0.170 ± 1.38	-0.176 ± 0.94	-0.149 ± 0.57
	R	-0.183 ± 1.97	-0.151 ± 0.94	-0.208 ± 1.25	-0.233 ± 0.85	-0.216 ± 1.91	-0.283 ± 0.721	-0.204 ± 2.10	-0.196 ± 0.22	-0.196 ± 0.12

Table 3.
Mean and standard deviation of maximum and minimum ankle moment (N·m/kg) on left and right limb (N=15)

Moment	Limb	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0% BW	5% BW	10% BW	0% BW	5% BW	10% BW	0% BW	5% BW	10% BW
Sagittal Max.[a]	L	0.166 ± 1.20	0.303 ± 1.35	0.176 ± 0.99	0.0837 ± 0.44	0.240 ± 0.17	0.198 ± 1.22	0.185 ± 0.94	0.235 ± 0.12	0.221 ± 1.37
	R	0.241 ± 1.97	0.308 ± 0.55	0.212 ± 0.36	0.132† ± 1.28	0.0905† ± 0.53	0.137†§ ±0.15	0.244‡ ± 1.37	0.296‡ ± 1.37	0.314‡Ψ§ ± 0.46
Sagittal Min.[b]	L	-1.515 ± 2.83	-1.502 ± 0.63	-1.523 ± 1.91	-1.457 ± 0.45	-1.518 ± 0.45	-1.589 ± 1.65	-1.075 ± 0.59	-1.134 ± 0.74	-1.036 ± 1.96
	R	-1.472 ± 0.97	-1.437 ± 0.53	-1.478 ± 0.35	-1.402 ±1.66	-1.458 ± 0.23	-1.570 ± 0.47	-1.124†‡ ±1.72	-1.071†‡ ± 0.75	-1.243†‡ ± 1.77
Frontal Max. [c]	L	0.0404 ± 0.24	0.0522 ± 0.88	0.829 ± 1.55	0.126 ± 0.45	0.211 ± 1.23	0.194 ± 1.22	0.224 ± 1.75	0.242 ± 1.37	0.269 ± 0.15
	R	0.0482 ± 0.11	0.0767 ± 0.39	0.1026 ± 0.66	0.0816† ± 0.75	0.104† ± 1.66*	0.0920 ± 0.55*	0.148†‡ ± 0.49	0.169†‡ ± 0.55*	0.196†‡ ± 0.64*
Frontal Min. [d]	L	-0.348 ± 0.57	-0.311 ± 0.72	-0.194 ± 0.45	-0.157 ± 0.94	-0.0471 ± 0.54	-0.0616 ± 0.57	-0.0776 ± 0.95	-0.0784 ±0.37	-0.0561 ± 0.86
	R	-0.206 ± 0.95	-0.203 ± 0.22	-0.204 ±0.71	-0.0788 ± 0.45	-0.0123 ± 0.59	0.0920 ± 0.63	-0.0451†‡ ± 0.47	-0.0793† ± 0.79	-0.0250† ± 0.32
Transverse Max. [e]	L	0.0355 ± 0.45	0.0812 ± 1.27	0.04509 ± 0.27	0.0322 ± 0.44	0.0331 ± 1.79	0.0198 ± 0.57	0.0245 ±0.93	0.0334 ± 1.29	0.0588 ± 0.32
	R	0.0430 ± 0.53	0.0528 ± 0.34	0.0201 ± 0.99	0.0212† ± 0.33	0.0093 ± 0.51	-0.1014 ± 0.84	0.0065 ± 0.85	0.0377 ± 0.17	0.0204 ± 1.33
Transverse Min. [r]	L	-0.196 ± 0.57	-0.1577 ± 0.98	-0.246 ± 0.25	-0.260 ± 0.11	-0.197 ± 0.75	-0.238 ± 0.19	-0.168 ± 0.63	-0.183 ± 1.74	-0.165 ± 0.57
	R	-0.201 ± 1.92	-0.162 ± 0.36	-0.255 ±0.37	-0.236 ± 0.16	-0.216 ± 0.41	-0.2856 ± 0.73	-0.206 ± 0.45	-0.209 ± 0.72	-0.199 ± 0.78

a	peak dorsiflexor moment in sagittal plane
b	peak plantarflexor moment in sagittal plane
c	peak inversion moment in frontal plane
d	peak eversion moment in frontal plane
e	peak internal rotation moment in transverse plane
f	peak external rotation moment in transverse plane
Ψ	P < 0.05 vs. 0% BW –Tukey post-hoc test
§	P < 0.05 vs. 5% BW –Tukey post-hoc test
†	P < 0.05 vs. Flat-heeled –Tukey post-hoc test
‡	P < 0.05 vs. 3 cm High-heeled –Tukey post-hoc test
*	P < 0.05 as comparing left with right limb – Independent t-test

DISCUSSION

Specific joint forces and moments are related to the measures of altered or pathological gait or movement. An analysis on kinetic parameters during the gait with high-heeled shoes and asymmetrical load helps to gain a lucid understanding of the musculoskeletal system of the body and its relationship with asymmetrical load carriage and raised heel. The current study was conducted to examine the combined effect of asymmetrical load carriage on lower extremities joint kinetics during normal and high-heeled walking in young healthy high-heeled shoes wearers.

Loaded limb vs. unload limb

Results of this study revealed that asymmetrical load carriage caused more remarkable changes in the musculoskeletal system than symmetrical loading. This is due to an imbalance from the load concentrated one side causing a shift of the centre of mass and lateral trunk bending away from the loaded shoulder. Kellis and Arampatzi[11] have examined various carrying methods and concluded one hand held carrying method has most deleterious effect on gait characteristics. The results of present study suggest that asymmetrically carried load altered joint kinetics on loaded and unloaded limb differently during walking. An interesting finding was that the difference between the loaded and unloaded limb occurs only during high-heeled gait.

Larger ankle inversion moment was displayed in unloaded limb during high-heeled gait with a load heavier than 5% BW. Fuller[12] suggested that the increased inversion moment is one of main causes of lateral ankle sprain, thus, an unloaded limb may be exposed to ankle injury more than a loaded limb during walking with an asymmetrical load. Asymmetrical loading causes the trunk to become laterally flexed with large compensational changes taking place at the adjacent joint, the hip. It has been reported that a load increases activity of hip extensors[5], thus, larger increase in the hip extensor moment on loaded limb compared to unloaded limb was expected. However, no significant difference was found between the two limbs in hip moment. Postural changes of the trunk affect both loaded and unloaded limb. The asymmetrical load carriage during high-heeled gait not only alters the limb on the loaded side but also puts equal or even larger stresses on the unloaded limb.

Shoes Effect on Kinetics of the loaded lower limb

Peak hip flexion moment did not show any significant changes with the heel height increase in all loading conditions while peak hip extensor moment increased as participants walked with high-heeled shoes in all loading conditions. Esenyel et al.[13] and Hwang et al.[14] also reported a similar finding. Participants displayed similar magnitude in peak hip flexion moment between the shoe conditions but displayed a prolonged in duration when wearing high-heeled shoes. Esenyel et al. suggested that the hip flexor torque prolongation is related to an increase in the overall concentric work of the proximal hip flexor muscles, which aids in limb acceleration. Evidence explaining a need for the prolongation of hip flexor muscles is the decrease of hip joint force. The present study found a decrease in the hip anterior joint force with the increase in heel height. More specifically, during walking of 3 cm high-heeled shoes and carrying a load of 10% BW decreased hip anterior force indicating decrease in acceleration of the limb, and with a load of 5% BW 9 cm high-heeled shoes decreased hip force. High-heeled shoes and load together decrease limb acceleration during swing phase and cause hip flexor muscles to work harder.

Regardless of the load carriage, hip extensor moment increased when participants walked with high-heeled shoes. Increase in hip extensor moment generated greater hip posterior joint force. During the high-heeled walking, the gluteus maximus, a major hip extensor, produced the large force to support the body weight by generating extension moment in early stance and by controlling hip flexion speed in terminal swing. This was confirmed by a study conducted by Son et al[15]. They examined the lower extremity muscle activities during walking in high-heeled shoes using electromyography (EMG) and reported an increased muscle activity of gluteus maximus during high-heeled walking with 9 cm high-heeled shoes.

In 5% BW loading condition, only 9 cm high-heeled shoes influenced hip joint forces, but in 10% BW loading condition, both 3 cm and 9 cm high-heeled shoes influenced joint force similarly. This result suggests that when the asymmetrical load was carried during locomotion, changes in joint kinetics were evidenced at higher heel conditions.

Knee, as an adjacent joint to the ankle that undergoes most prominent changes in joint kinematics and kinetics, must be altered to compensate for the exaggerated plantarflexed posture and minimize the impact to transfer to proximal joints. Knee during high-heeled gait demonstrated larger extensor moment and varus moment. With high-heeled shoes, knee adduction was increased during stance contributing to medial shift in the location of the centre of pressure[13]. Ground reaction force, then, is placed more medially creating larger knee varus moments. Correspondingly, knee medial joint force increased to ensure knee stability in frontal plane was increased. Similar finding was reported by Esenyel et al[13]. Participants with high-heeled shoes of any height generated larger knee extensor moment in sagittal plane. The body controls this moment with passive force in anterior direction. This explains the increased muscle activity of rectus femoris, an important knee extensor, during stance reported by Son et al.[15]

Increased knee moment and force are thought to be closely related to the development of osteoarthritis (OA)[16]. Since OA of the knee is twice as common in woman as it is in men and usually occurs bilaterally, the high-heeled shoes may predispose to OA of the knee because both load carriage and high-heeled shoes walking change knee kinetics. However, in the other hand, it is important to emphasize the importance in knee moment increases since the larger knee moment stabilizes the joint and transfers the centre of mass of the body as the limb is loaded during gait.

Ankle undergoes most significant changes in joint angle in walking with high-heeled shoes due to the raised heel height. As previously reported by other scholars[13], an excessive increase in plantarflexion resulted decrease in ankle moment since smaller propulsive moments were required at take-off. Although magnitudes of the joint moment varied between the different loaded conditions, a decrease in ankle moment was showed in all conditions of high-heeled shoes walking. The role of the ankle plantarflexors during the gait is to contribute to knee stability, provide ankle stability, restrain the forward rotation of tibia on the talus during stance phase[17, 18], therefore, the reduced ankle plantar flexor moments may hinder it to carry out its function. Decrease in ankle plantarflexor activity limits the ankle moment which was evident in high-heeled gait. Ankle moments are known to be limited during walking in patients with patients with neuromuscular disorder or elderly persons[18]. Therefore, the high-heeled shoes may promote gait deviations similar to those generated from other medical conditions or aging. This may also contribute to the increased incidence of falls and injuries among female population. This study finding agrees with the observations of Esenyel et al. who also reported a reduction in ankle plantarflexor moment. They suggested that the plantarflexors are in a less favourable position for power and work generation as raised heel shortened gastrocnemius and soleus muscles.

Similar to the data presented by Esenyel et al.[13], it was found that peak ankle anterior joint force increased with increased heel heights. Increase in soleus muscle activity was reported by Stefanyshyn et al.[19] with heel height during walking which is an evidence supporting the ankle anterior joint force increase since soleus is a main plantarflexor. This result may look contradicting since plantarflexor moment decreased with increase in heel height. However, the length of moment arm of the Achilles tendon decreases as ankle becomes plantarflexed with high-heeled shoes, therefore, despite an increase in force in the

Achilles tendon due to increased soleus muscle activity, decrease in moment was depicted. In addition, with a load carriage, the increase in ankle anterior joint force was greater in magnitude. During unloaded walking, significant difference in ankle force was found only between flat-heeled shoes and high-heeled shoes, meaning no difference between 3 cm and 9 cm high-heeled shoes, but during loaded walking, significant differences were found between all shoes conditions, meaning 9 cm high-heeled shoes further increased the ankle force than 3 cm high-heeled shoes when load was carried.

Loads Effect on Kinetics of the loaded lower limb

Asymmetrical loading affects the body by destructing the body's symmetry and challenges the balance. It was reported from a previous study that a maximum acceptable weight for asymmetric lifting is significantly lower than those for symmetric lifting[20]. Few studies investigated the effect of asymmetrical loading during walking or lifting in order to highlight biomechanical changes caused by asymmetrical loading compared to symmetrical loading, however, many of them have focused only on trunk biomechanics.

The changes in joint moment in the frontal plane occurred in hip joints as previously reported by Choi et al.[21] from their study of side-loaded carriage during walking. Present results also agreed with Choi et al., in that hip abductor moment was smaller with large load. Furthermore, hip abductor moment also showed the similar trend during the high-heeled gait with both 3 cm and 9 cm high-heeled shoes. Since asymmetrical load caused the trunk to bend laterally away from the load, the body's COM is more inclined to the opposite side of the load carriage. Thus, as load weight increased, hip abduction was limited to minimize movement of body's centre of mass.

The changes in hip joint in the sagittal plane also demonstrated a significant change with the asymmetrical load. In sagittal plane, a load of 10% BW increased hip posterior force. Chow et al.[22] reported from their backpack study that with a load the peak hip power generation increased. Increased hip posterior force during terminal stance is created by the larger hip power generation as pelvic rotation is restricted by the backpack. Participants in the present study revealed a similar result as that occurred by the backpack from the study by Chow et al. Correspondingly, the increase in hip flexor moment with the load of 10% BW was evidenced. Again, the finding of Chow et al. supports present finding by concluding in their gait analysis with backpack that the critical load for the peak hip flexor moment was 10% BW.

Knee adductors generated the largest moment when 10% BW load was carried in 9 cm high-heeled shoes walking. It has been reported previously that in normal gait, movements of the knee in the frontal plane is negligible since its magnitude is too small[23], but the present result found the asymmetrical load carriage of 10% BW altered the knee moment in frontal plane. Unlike from symmetrical loaded gait including walking with no load, the frontal plane joint kinematics and kinetics are altered in asymmetrical loaded gait as the load is applied to only one side of the body and bends the trunk.

Choi et al.[21] studied the effect of the weight of the side loaded carriage in walking and reported an increase in knee extensor moment during stance phase. The finding from present study agrees with the study result conducted by Choi et al. The maximum extensor moment was larger during walking with a load 10% BW in both high-heeled gaits. The larger knee extensor moment was necessary to generate the lift during terminal stance and to transfer the centre of mass of the body while counter balance the body for the side load imbalance.

Peak knee lateral joint force decreased during flat-heeled and 3 cm high-heeled walking, but it increased during 9 cm high-heeled walking. Increased peak knee lateral force with the increase in load weight was previously reported by Harman et al.[5] and Kinoshita[2]. Increase in the lateral force in knee was controlled by the increased knee adductor moment, which stabilizes the joint in frontal plane.

The increase in plantarflexor moment was reported from various previous load carriage studies in both asymmetrically[21, 24] and symmetrically carried load[22]. During walking with 10% BW load, plantarflexor moment increases to support the lower limb and propagate the swinging leg. Although plantarflexor moment showed an increase due to the load carriage similar to other studies, during high-heeled gait, the magnitude was considerably small. This is because while plantarflexor moment increased with increase in the load weight, it decreased with increase in the heel height. Another pattern that demonstrates the combined effect of high-heeled shoes and load carriage is ankle posterior joint force. During flat-heeled walking, ankle posterior joint force decreased with load weight increase, but during high-heeled walking, it increased with load weight. Robinson et al.[25] suggested that increase horizontal force at ankle restricts ankle movement since ankle motion is limited once ankle is fixed in the plantarflexed position from the high-heeled shoes. These are an outcome effect of the high-heeled shoes and asymmetrical load carriage combined. As mentioned earlier in the present paper, it was prominent that ankle joint is substantially affected by the high-heeled shoes and hip joint is substantially affected by the load carriage.

The inverted pendulum model of human gait suggests that changes in the lower limb moments are a result of demands of vertical support, horizontal balance and posture. An increasing load would be expected to cause an increase in the extension moments of all of the lower limb joints, to prevent the lower limb from collapse [26].The changes in the moments from the lower limbs support such belief since the peak knee extension and ankle platarflexor moments increasing with load to support the lower body. There was one exception, however, which is the hip extension moment in load response. It would be expected to increase with load carriage in response to the increased lower limb support and upper body stabilization requirements, but showed no significant increase. Chow et al. examined lower extremity kinetics during gait with load carriage in two groups, normal girls and the girls with idiopathic scoliosis and found that no significant difference in hip extension moment between two groups. It is suggested that this may be due to the changes in trunk posture, as the laterally placed load may result in an increased extension moment acting about the hip joint, despite the increase in forward trunk inclination seen with backpack load[27].

One of the limitations of this study was the load carrying side. People tend to carry an asymmetrical loading on dominant side, so participants whose dominant side for carrying a purse is not right would influence the data. Moreover because only one type of high-heeled shoes, a stiletto heel, was used in the present study, it should not be generalized for all high-heeled shoes since shoe construction and base of support at each sole are different among various types of women's footwear. Lastly, due to the increased levels of combined effect of independent variables, some of the associations may have occurred by chance, but it is likely that the comparisons with large effect size reflect the true effect.

CONCLUSION

The findings of this study indicated that the use of high heel shoes and asymmetrical loading alters the lower extremity kinetics during walking. These changes represented adaptive strategies that maintain limb stability as the ankle is forced into an exaggerated plantarflexed posture with the lateral trunk bending and substitute for the reduced plantarflexor function in limb advancement through the increased use of hip flexor activity. Asymmetical load carriage affected the loaded limb differently from unloaded limb in lower extremity kinetics interestingly only during high-heeled walking. Hip extensor moment increased with heel height increase but not with load weight increase. Knee extensor moment was affected by both high-heeled shoes and load carriage. Ankle plantarflexor moment decreased with high-heeled shoes but increased with load weight. As a result of high-heeled shoes and load carriage, knee extensor moment exaggerated and ankle plantrarflexor moment diminished. The changes appeared to be a considerable factor of potentially injurious forces that may underlie some of the proximal joint pain complaints of high-heeled shoes users. Furthermore, an additional load carried on one shoulder only exacerbates the alterations, therefore consideration is necessary when high-heeled shoes and load carriage combined are utilized for prolonged period.

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Article 3

COMBINED EFFECTS OF HIGH-HEELED SHOES AND LOAD CARRIAGE ON JOINT KINEMATICS AND KINETICS OF LOWER EXTREMITY DURING WALKING IN EXPERIENCED AND NOVICE HIGH-HEELED SHOES WEARERS

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Abstract

The combined effect of high-heeled shoes and asymmetrical load carriage on the temporospatial, lower extremity joint kinematics, and kinetics parameters during walking and static balance tests was investigated between 15 experienced high-heeled shoes wearers and 15 novice wearers. Kinematic and kinetic data were collected when the participants walked in their preferred speed in 9 conditions created from three heights of shoes and three weights of symmetrical load. The results from the present study verified that the participants in novice high-heeled shoes wearer group have longer double support time and shorter stride length during 10% BW asymmetrical loaded walking than those in experienced group. The novice group walked with greater knee flexion angle and smaller knee range of motion than the experienced group. Also the novice group showed smaller peak knee flexor and ankle dorsiflexor moment than the counterpart group. The novice group scored lower in tandem and single stance balance test than the experienced group. Participants in novice group need to alter the gait pattern to adjust to high-heeled shoes so the balance is achieved during gait with asymmetrical loading.

INTRODUCTION

Surveys have shown that between 37% and 69% of women wear high heels on a daily basis[1]. As the number of women wearing high-heeled shoes increases in North America, high-heeled shoes and load carriage are employed more often. Previous studies on either high-heeled shoes or load carriage indicated that both alter gait patterns and raise a potential to generate joint pains[2,3]. The high-heeled shoes affect temporospatial parameters[4, 5], such changes are increased double stance time and decreased walking velocity, step length, and width. These changes in the gait specific parameters are similar to those observed by elder population or patients with musculoskeletal disorders[6,7]. High-heeled shoes also results in increase in ground reaction force and changes the relative orientation of the skeletal structures of the lower extremity joints especially the ankle joint[8]. On the other hand, studies on the effects of load carriage on gait have shown changes in temporospatial parameters[3], lower limb joint reaction force, and ground reaction force[9]. Furthermore, if the load is carried asymmetrically, which is a carrying method most frequently used among women, changes in the gait pattern and body posture are larger[10]. High-heeled shoes increase ankle plantarflexion and knee flexion angle, and asymmetrically carried load increases knee flexion and decreases hip extension angle[5]. Both factors shift centre of mass and challenge the balance during gait.

Despite the number of studies that have addressed either the effect of high-heeled shoes or asymmetrical load carriage during gait, no study has looked at the combined effect of two factors. In addition, although numerous high-heeled shoes studies have recommended studying the experience factor to understand high-heeled gait thoroughly since habitual high-heeled shoes wearers would have generated an adaptive mechanism, there is still lack in research in this area. Performing the gait analysis by grouping participants according to the amount of experience in wearing high-heeled shoes would help to control the intersubject variability and to facilitate identification of accommodations in gait to high-heeled foot wear.

Hence, the purpose of this study is to investigate the combined effect of high-heeled shoes and asymmetrical load carriage on lower extremity joint kinematics during walking in experienced and novice high-heeled shoes wearers. It was expected that the findings from the study would add an understanding to the gait and posture pattern in this population and the adaptation of the gait and posture as wearing high-heeled shoes experience.

METHODS

Participants

Fifteen experienced high-heeled shoes wearers and fifteen novice high-heeled shoes wearers participated in the study. All participants were healthy females aged between 19 and 30 and free from musculoskeletal disorders. Experienced high-heeled shoes wearers have at least 3 years of experiences in wearing high-heeled shoes more than 3 times a week and novice high-heeled shoes wearers have either never worn high-heeled shoes or wear it no more than once a month. All participants were categorized into either experienced high-heeled shoes wearer or novice, inexperienced, high-heeled shoes wearer determined by the researcher from a questionnaire provided prior to the testing. Participants' descriptive data are presented Table 1. All participants received information on participation requirements and testing procedures prior to the testing and signed a consent form agreeing to take part in research.

Shoes and load characteristics

A pair of flat-heeled shoes of 1.1 cm sole was used for the control (Vans Inc., California, USA). Two pairs of high-heeled shoes were pin-pointed stiletto heel shoes with heel height measured as 3.0 cm and 9.0 cm respectively (Jones Apparel Group Inc., NY, USA). The base of the tip of stiletto heel was 0.9 cm^2. High-heeled shoes had leather upper part where as flat-heeled shoes had canvas upper part. Three different sized shoes, 6, 7.5, and

9, were prepared to accommodate different foot sized participants. Three loading weights of 0%, 5%, and 10% of participant's body weight (BW) were utilized for the testing. A small nylon woman's purse sized 26.7 cm (L) x 3.8 cm (W) x 16.5 cm (H) was used to carry different weights of load on subject's one shoulder (model: 7606 Lulu, Le Sportsac Inc., USA). A load of 10% of BW was set as a maximum load according to previous load carriage studies that have suggested the 10% of body mass as a critical mass altering the gait and balance and showing significant effect on participants when carried on one shoulder[11]. Circular shaped metal weights were placed into the purse and body of the bag was placed between the trunk and upper arm. Nine different shoes-and-loads-combined conditions were tested in randomized order to examine the combined effect of high-heeled shoes and asymmetrical load.

Experimental protocols

Participants were asked to walk across the testing area of approximately 8 m at her most comfortable speed. Data was collected from five successive trials for each condition for further analysis. Three-dimensional motion of the walking trials were captured using a VICON Motion Analysis System with nine high-speed infra-red cameras (Vicon MX-13, Oxford Metrics, Oxford, UK) in order to examine the changes in lower extremity joint angles between two participant groups. Participant's walking movement was captured at 200 Hz. All participants wore a tight shorts and t-shirt. 43 reflective markers were placed on the anatomical land marks of participant's body according to University of Ottawa Motion Analysis Model (UOMAM) marker set[22,23]. Kinetic data were collected using three force plates (models 9286AA, Kistler Instruments Corp, Winterhur, Swtz; FP 4060-08, Bertec Corporation, Columbus, OH, USA) at 1000 Hz. The force plates were embedded in the middle of walkway in such a way that participants could step on each plate one after the other within their steps of walking. After the walking trials, two static balance tests, single leg stance and tandem leg stance tests were performed. All participants stood on their right leg for the single leg balance test. Time for each stance test was measured.

Data processing and analysis

Two consecutive strides for each right and left leg were analyzed for both kinematics and kinetics data, and all collected data were normalized to gait cycle for further analysis. Measurements of foot contact and toe-off were obtained by visually inspecting the position of the virtual markers on the heel and toe. VICON Nexus software (v1.3) along with UOMAM marker set was used to obtain lower-limb kinematic measurements of hip, knee, and ankle angles in sagittal plane. Computed joint angle data from Nexus was exported to Excel (Microsoft, Washington, USA) to find a maximum and minimum angle each trial. For each participant, kinematic and kinetic parameters of each stride were averaged across the 5 trials for each walking condition. The parameters were finally averaged across all participants of each group.

Collected and processed joint kinematic and kinetic data from two groups were compared using independent samples *t*-test. The level of significance was chosen as $p < 0.05$. The statistical analysis was utilized using a Statistical Package for Social Sciences (SPSS) version 16.0 software for Windows (SPSS Science, Chicago, Illinois).

RESULTS

Temporospatial Parameters

No significant differences were found in age, height, and body mass between experienced high-heeled shoes wearers group and novice group (Table 1). A series of paired sample t-test between experienced and novice groups revealed that there were no significant differences in lower extremity joint angles in the sagittal plane and temporospatial parameters during all flat-heeled conditions between the groups.

Table 1.
Anthropometric measurements of experienced (N=15) and novice (N=15) groups.

	Experienced (N=15)	**Novice (N=15)**	***P*-value**[a]
Age (yr)	24.7 (3.53)	22.7 (3.15)	0.388
Height (cm)	162.2 (3.91)	163.2 (5.88)	0.517
Body mass (kg)	54.9 (6.66)	56.8 (8.45)	0.164

[a] *P*-values from paired sample *t*-test are indicated.

With 9 cm high-heeled stiletto shoes, stride time (p = 0.021, 0%; 0.001, 5%; 0.006) and double support time (p = 0.022, 0%; 0.030, 5%; 0.012, 10%) increased while stride length (p = 0.001, 0%; 0.011, 5%; 0.029, 10%) and step length (p = 0.003, 0%; 0.012, 5%; 0.014, 10%) decreased in all loading conditions for the novice group (Table 2). Walking in flat-heeled or 3 cm high-heeled shoes did not show significant change in temporospatial parameters between the two groups.

Significant differences were found in the tandem leg test at all loading conditions between the two groups. The single leg stance test at no loading and 5% BW loading conditions showed significant differences between the two groups (Table 3). In 3 cm high-heeled shoes, the novice group scored lower in tandem leg stance at 5% BW loading and in single leg stance test at 10% BW loading conditions.

Kinematic Parameters

Peak joint angles in the sagittal plane showed significant differences between the groups during both 3 cm and 9 cm high-heeled gaits (Table 4). No significant differences in peak angles were found during flat-heeled walking in all loading conditions between the two groups. Most significant differences occurred during 10% BW loading conditions. At 10% BW loading condition, no significant differences in peak hip flexion and extension angle were found between two groups. Peak knee flexion angle was greater in the novice group while peak knee extension angle was greater in the experienced group. Peak ankle plantarflexion angle was greater in experienced group and peak dorsiflexion angle did not differ significantly between the two groups.

Kinetic Parameters

Similar curve profiles, but with different peak moment values, were found for three joints in the sagittal planes between groups. Hip and knee extensor moment reached its peak around 10-20% of the gait cycle when the body is pulled up to the next step. Ankle plantarflexor moment reached peak around 55-60% of the gait when the foot was pushed off the ground. Peak joint moments in the sagittal plane during walking with 10% BW load in 9 cm and 3 cm high- heeled shoes for both groups are summarized in Table 5. Similar to kinematic results, no significant differences in peak hip moments were found between the groups. In 3 cm high-heeled gait, the novice group had smaller peak knee flexor moment than that of the experienced group but in 9 cm high-heeled gait, no differences were found. Peak ankle dorsiflexor moment was larger for experienced group in 9 cm high-heeled walking while smaller in 3 cm high-heeled walking.

Table 2.
Summary of temporospatial parameters for experienced (N=15) and novice (N=15) groups

Parameters	Groups	Condition								
		Flat-heeled shoes			3 cm high-heeled shoes			9 cm high-heeled shoes		
		0 % BW	5% BW	10% BW	0 % BW	5% BW	10% BW	0 % BW	5% BW	10% BW
Stride Time (s)	E	0.96 (1.11)	1.03 (0.92)	1.00 (1.13)	1.01 (2.07	1.03 (0.41)	1.05 (2.48)	1.03 (0.97)	1.03 (0.79)	1.02 (1.98)
	N	1.03 (2.21)	1.02 (1.20)	0.99 (1.03)	1.05 (1.99)	1.01 (0.56)	1.02 (1.41)*	1.15 (0.33)*	1.15 (0.41)*	1.12 (0.88)*
Stride Length (m)	E	1.48 (0.16)	1.60 (0.98)	1.60 (0.77)	1.55 (0.71)	1.63 (1.19)	1.49 (0.54)	1.56 (0.44)	1.49 (0.18)	1.45 (0.10)
	N	1.47 (0.73)	1.46 (0.82)	1.50 (0.91)	1.47 (0.55)	1.43 (0.59)	1.49 (0.25)	1.27 (0.97)*	1.30 (0.75)*	1.29 (0.68)*
Double Support Time (S)	E	0.15 (0.87)	0.14 (0.36)	0.13 (0.11)	0.19 (0.83)	0.19 (0.88)	0.21 (1.16)	0.25 (0.14)	0.22 (0.21)	0.24 (0.17)
	N	0.15 (0.45)	0.17 (0.83)	0.17 (0.81)	0.20 (0.23)	0.20 (0.18)	0.24 (0.96)	0.27 (0.33)	0.30 (0.96)*	0.31 (0.59)*
Step Length (m)	E	0.75 (0.08)	0.77 (0.83)	0.76 (1.02)	0.75 (0.05)	0.80 (0.12)	0.72 (0.07)	0.75 (0.07)	0.74 (1.06)	0.69 (1.18)
	N	0.71 (0.12)	0.71 (0.50)	0.75 (0.74)	0.73 (0.45)	0.74 (0.36)*	0.71 (0.55)	0.62 (0.51)*	0.62 (0.36)*	0.60 (0.96)*

E	experienced high-heeled shoes wearer group
N	novice high-heeled shoes wearer group
*	$p < 0.05$ paired sample *t*-test

Table 3.
Values for the static balance tests in experienced (N=15) and novice (N=15) groups

Heel Height	Load weight (BW)	Single leg Stance			Tandem leg Stance		
		Experienced (s)	Novice (s)	P-value	Experienced (s)	Novice (s)	P-value
Flat-heeled	0 %	28.1 (5.26)	32.7 (8.33)	0.845	26.3 (8.53)	25.6 (5.62)	0.823
	5 %	31.3 (7.53)	33.9 (8.19)	0.296	30.2 (7.21)	27.7 (8.39)	0.730
	10 %	21.5 (6.87)	23.4 (8.33)	0.844	14.7 (11.2)	22.5 (9.99)	0.236
3cm-heeled	0 %	14.3 (5.99)	11.4 (10.5)	0.364	12.6 (5.87)	11.7 (6.44)	0.433
	5 %	16.3 (8.33)	10.3 (6.29)	0.945	14.2 (5.74)	5.35 (6.49)	0.021*
	10 %	10.2 (5.38)	4.74 (8.19)	0.043*	5.22 (5.86)	4.23 (4.96)	0.396
9cm-heeled	0 %	4.34 (4.22)	1.95 (5.28)	0.002*	3.65 (4.65)	1.12 (2.11)	0.003*
	5 %	4.62 (2.69)	2.12 (3.94)	0.002*	8.94 (5.23)	1.33 (4.94)	0.006*
	10 %	2.27 (4.34)	1.32 (3.27)	0.755	2.01 (4.28)	1.00 (2.02)	0.003*

* $p < 0.05$ paired sample *t*-test

Table 4.
Mean and standard deviation of maximum peak angles (degrees) during 10% BW loaded gait for the experienced (N=15) and novice group (N=15)

Joint	Peak Angle	Heel heights	Experienced	Novice	P-value
Hip	Flexion	9 cm-heeled	40.48 (3.73)	42.29 (6.33)	0.064
		3 cm-heeled	40.14 (3.94)	41.62 (4.32)	0.546
		Flat-heeled	38.02 (3.11)	39.01 (4.29)	0.834
	Extension	9 cm-heeled	-8.466 (3.10)	-11.08 (5.07)	0.042
		3 cm-heeled	-8.973 (2.67)	-12.81 (3.63)	0.871
		Flat-heeled	-9.473 (4.64)	-11.94 (4.36)	0.966
Knee	Flexion	9 cm-heeled	55.37 (9.87)	67.45 (11.2)	0.028*
		3 cm-heeled	63.17 (7.24)	70.78 (9.22)	0.023*
		Flat-heeled	68.23 (4.63)	69.44 (6.96)	0.097
	Extension	9 cm-heeled	-0.565 (0.47)	22.02 (7.68)	0.007*
		3 cm-heeled	2.501 (0.24)	21.97 (4.29)	0.008*
		Flat-heeled	5.263 (0.63)	19.23 (9.94)	0.059
Ankle	Dorsiflexion	9 cm-heeled	-9.087 (4.35)	-2.678 (2.43)	0.189
		3 cm-heeled	1.080 (2.10)	6.233 (2.56)	0.444
		Flat-heeled	3.252 (0.52)	5.522 (4.64)	0.754
	Plantarflexion	9 cm-heeled	-39.11 (4.22)	-35.66 (10.2)	0.043*
		3 cm-heeled	-33.97 (1.25)	-24.04 (4.52)	0.031*
		Flat-heeled	-31.46 (3.46)	-26.37 (3.22)	0.059

* $p < 0.05$ paired sample *t*-test

Table 5.
Mean and standard deviation of maximum peak moments (N·m/kg) during 10% BW loaded gait for the experienced (N=15) and novice group (N=15)

Joint	Peak Moment	Heel Heights	Experienced	Novice	P-value
Hip	Flexion	9 cm-heeled	0.0170 (0.003)	0.0168 (0.005)	0.623
		3 cm-heeled	0.0193 (0.004)	0.0170 (0.002)	0.545
		Flat-heeled	0.0199 (0.008)	0.0189 (0.006)	0.934
	Extension	9 cm-heeled	-0.0265 (0.003)	-0.0225 (0.002)	0.142
		3 cm-heeled	-0.0232 (0.001)	-0.0255 (0.003)	0.623
		Flat-heeled	-0.0281 (0.009)	-0.0244 (0.006)	0.111
Knee	Flexion	9 cm-heeled	0.00746 (0.005)	0.00831 (0.000)	0.245
		3 cm-heeled	0.01033 (0.008)	0.00685 (0.002)	0.002*
		Flat-heeled	0.00932 (0.003)	0.00432 (0.008)	0.351
	Extension	9 cm-heeled	-0.0292 (0.001)	-0.0298 (0.004)	0.363
		3 cm-heeled	-0.0216 (0.003)	-0.0255 (0.004)	0.045
		Flat-heeled	-0.0132 (0.001)	-0.0232 (0.001)	0.627
Ankle	Dorsiflexion	9 cm-heeled	0.00654 (0.000)	0.00205 (0.000)	0.001*
		3 cm-heeled	0.00287 (0.000)	0.00494 (0.001)	0.001*
		Flat-heeled	0.00112 (0.001)	0.00363 (0.004)	0.664
	Plantarflexion	9 cm-heeled	-0.0259 (0.002)	-0.0265 (0.002)	0.562
		3 cm-heeled	-0.0327 (0.005)	-0.0343 (0.001)	0.252
		Flat-heeled	-0.0312 (0.001)	-0.0384 (0.006)	0.734

* $p < 0.05$ paired sample *t*-test

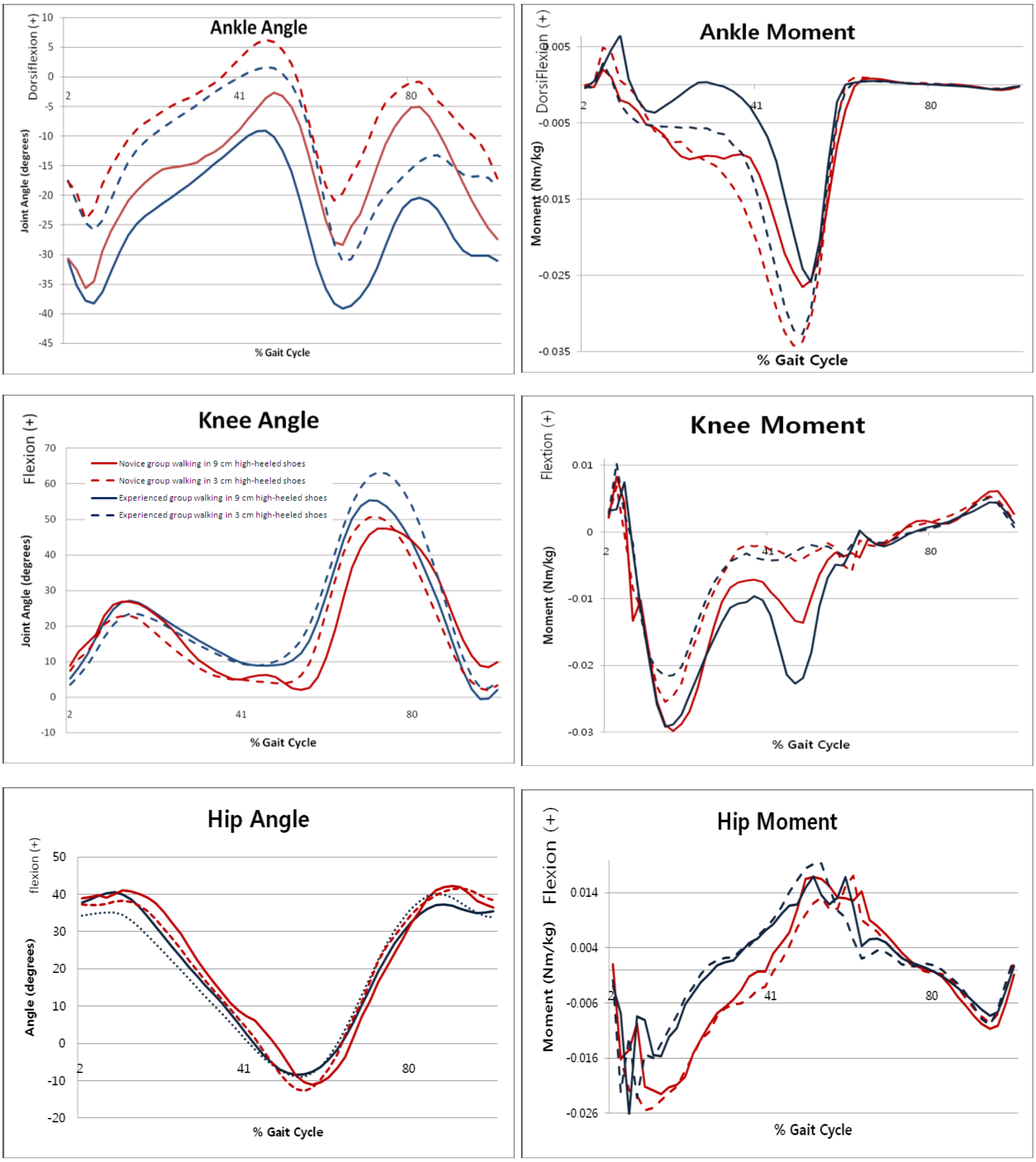

Figure 1. Ankle, knee, and hip angles and moment of force in sagittal plane during walking with a load of 10% BW

DISCUSSION

The purpose of this study was to investigate the combined effect of high-heeled shoes and asymmetrical load carriage on lower extremity joint kinematics during walking in experienced and novice high-heeled shoes wearers. The results of this study demonstrated that when experienced and novice high-heeled shoes wearers wear high-heeled shoes and carry asymmetrical load, the lower extremity joint kinematics and kinetics of the two groups showed considerable and significant differences.

Temporospatial parameters

The novice group showed a shorter stride length when 9 cm high-heeled shoes were worn. 3 cm high-heeled shoes did not affect the stride length and step length. A similar study done by Opila-Correia[5] also reported a shorter stride length in novice group when participants walked with 6.1 cm high-heeled shoes. It has been suggested that the stride length and step length are related to balance, when balance is challenged during gait due to irregular surfaces, footwear, or aging shorter stride and step length were evidenced[6,7]. Participants with no experience wearing high-heeled shoes were more careful in taking steps during the gait due to the unstable high-heeled shoes. It seems that high-heeled shoes decreased the ability to control the posture, not only the lower extremity but also the upper trunk in both sagittal and frontal plane. An increase in double support time for the novice group also supports the notion. Previous studies with elder participants were in agreement with such findings, and the increase in double support time and decrease in stride length are in fact a stabilizing adaptation for them[12]. This is once again supported by the results from static balance tests. Single leg and tandem leg stance tests revealed that participants in the novice group performed poorer compared to the experienced group. In 9 cm high-heeled shoes, static stability is more challenged due to the small base of support and shift of centre of mass in both groups. However, the experienced group was able to perform better than the novice group since the experienced group has developed balance mechanism from their previous experience such as balance on a moving bus or walking up and down the stairs. Through such experience, the participants in experienced group could have a better control over muscles that are responsible to maintain a stable posture even on a small supporting base. Another interesting point is that there is no significant difference in the measurements between the two groups in 9 cm high-heeled shoes when 10% BW was carried. Therefore, only heel height of the shoes, but not the load carriage, caused distinguishable temporospatial parameter changes during walking for the participants in the novice group.

Experience effect on Joint Kinematics

When 10% BW load was carried asymmetrically, both 3 cm and 9 cm high-heeled shoes altered the peak knee and ankle joint angles in the sagittal plane. As previously stated by Opila-Correia[5], no significant differences in hip angle between groups were found in the present study. Participants in the novice group demonstrated a smaller peak plantarflexion angle and a greater peak knee flexion angle when 9 cm high-heeled shoes were worn. The raised heel caused ankle to plantarflex causing an increase in the vertical shock loading during gait[13]. This increased load can be attenuated by changes in the kinematics of body or by direct absorption by the soft tissues[11]. To prevent the acceleration of tissue degeneration, compensational changes in joint kinematics is achieved by increasing flexion at more proximal joints. The novice group was affected by the raised heel height more significantly than the experienced group because the body was not prepared for high-heeled gait, the novice group demonstrated greater knee flexion angle as a response to the high-heeled shoes. The novice group demonstrated smaller knee range of motion than that of the experienced group in both 3 cm and 9 cm high-heeled gait. A reduced knee range of motion is considered as stiffed joint[16] and has been reported in the gait studies on female elders[14] or patients underwent arthroplasty[15]. The novice group, when compared with the experienced group, showed more stiffed knee joint affecting the gait pattern. Kinematics alterations made by the novice group for the compensations of increased plantarflexion may not be as an optimum as it showed by the experienced group.

Experience effect on Joint Kinetics

During high-heeled gait with 10% BW load carriage, no significant difference was found in hip joint kinetics between the experienced and novice group as it was witnessed in the kinematic data. Results indicated that the hip joint was not the main compensatory site for the changes in the ankle from raised heel height. Similar conclusion was made by Hansen and Childress[17] stating that the compensation for wearing heels would appear to occur lower in the body at the knee and ankle, rather than in hip and lumbar region.

Peak knee flexor moment was greater in the experienced group during 3 cm high-heeled gait while no difference was found in 9 cm high-heeled gait. Peak knee flexor moment was reached within first 5% of the gait cycle which is a starting of the loading response phase. An increased knee flexor moment during the loading response phase promoted knee flexion for the shock absorption, therefore, greater knee flexor moment demonstrated by the experienced group indicated the efficient shock absorption when compared to the novice group. The function of the knee as a shock absorber was previously reported by Bresler and Berry[18] from their energy studies which concluded that both knee and ankle contribute equally to shock absorption. An interesting but easily neglected feature in the knee moment profile is second peak knee extensor moment during 9 cm high-heeled gait. Although peak knee extensor moment did not show significant difference between the two groups, the difference in the second peak (figure 1) is noticeable. This is also greater in the experienced group than the novice group. Lee et al.[19] suggested that with increased heel height, knee extensors revealed larger muscle activity to stabilize the knee. Both groups showed increased knee extensor moment, however the experienced group generated noticeably larger extensor moment in 9 cm high-heeled gait suggesting that experienced high-heeded shoes wearers may be more active in controlling muscles to protect the joint.

While peak ankle plantarflexor moment did not show a significant difference between the two groups, peak ankle dorsiflexor moment showed significant difference in both 3 cm and 9 cm high-heeled gait. The peak ankle dorsiflexor moment was reached in loading response phase. During the loading response, ground reaction force produces a plantarflexion moment at the ankle joint[20] which is controlled by eccentric activity in the ankle dorsiflexors. The experienced group had significantly greater ankle dorsiflexor moment than the novice group, suggesting that the eccentric activity was increased effectively to counter balance the plantarflexion moment, in turn, limits unnecessary ankle movement in the sagittal plane and stabilizes the joint from the shifted centre of mass caused by raised heel height.

It is acknowledged that the present study has several limitations. High-heeled shoes used during the data collection may deform as more participants were tested. However, the order of participants being tested was randomized, the shoe deformation effect could be neglected. In addition, although all experienced high-heeled shoes wearers have history of wearing high-heeled shoes, the type of shoes worn may vary between the participants. However, from a study by Kerrigan et al[21], it has been reported that the footwear with raised heel affected the knee joint regardless of the style or types of high-heeled shoes.

CONCLUSION

In the present study it was found that the experienced and novice high-heeled shoes wearers developed gait adjustments during walking with high-heeled shoes and asymmetrical load in a similar way but with difference magnitude. The high-heeled shoes and load carriage together influenced on temporospatial parameters and static balance of the novice group more than the experienced group. Significant differences on sagittal joint kinematics and kinetics between the two groups were found in distal joints. Participants in novice group need to alter their gait pattern to adjust to the high-heeled shoes so balance is achieved during gait with asymmetrical loading. The baseline kinematic and kinetic data and possible compensatory strategies of women may enable the therapists and clinicians to understand the experience effect and to evaluate the female populations frequently using high-heeled shoes more accurately.

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Chapter 5: Conclusion

The present study examined the combined effect of high-heeled shoes and asymmetrical load carriage on lower extremity joint biomechanics in order to examine the altered gait and posture during walking among young healthy females. In addition, this study took participants' experience as a factor to further analyze the postural adaptation of walking with high-heeled shoes.

The results from this study indicated that both high-heeled shoes and asymmetrical load carriage caused alterations in temporospatial parameters, joint kinematics and kinetics during walking. More specifically, double support time and stride length increased while cadence decreased during walking with high-heeled shoes indicating more conservative walking pattern. The magnitude of alteration was greater when load of 10% BW was added. Increased plantarflexion was main cause of raised heel height. Ankle plantarflexor moment increased with high-heeled but decreased with load carriage. As a result of high-heeled shoes and load carriage, plantarflexor moment diminished, in addition knee extensor moment exaggerated further. From the kinetics data, it was evident that hip extensor moment increased with heel height increase but not with load weight increase, however, from the kinematics data, it was found that hip angle was affected by the asymmetrical load rather than the raised heel.

When comparing the measurements between experienced and novice high-heeled shoes wearers, noticeable differences in gait pattern were present. The high-heeled shoes and load carriage together had a significant influence on the temporospatial parameters and static balance for the novice group more than the experienced group. Specifically, the joint kinematics and kinetics in sagittal plane showed few distinguishable differences. The novice high-heeled shoes wearers undergo further alterations in their gait to adjust to the high-heeled shoes so their balance is achieved during the gait with the asymmetrical load.

The changes in gait characteristics evidenced from young healthy female participants. This study suggests that women when walking with high-heeled shoe and load carriage have adaptive strategies to maintain stability and to carry on steps for ambulation. Kinematics and kinetics changes at the lower extremity caused by the combined high-heeled shoes and load carriage might be a considerable factor of potentially injurious forces that may underlie some of the joint pain complaints of high-heeled shoes users. Prolonged walking in altered posture may accelerate pain or musculoskeletal disorders. Also, more increased load weight higher than 10% BW may further exacerbate the postural stability and increase risks of falls. The findings from this study recommend the users to avoid carrying heavy load when walking with high-heeled shoes, especially to those who have no experience in walking in high-heeled shoes.

Appendix 1.

Faculty of Health Science, School of Human Kinetics, University of Ottawa

Experience of Wearing High-heeled shoes Questionnaires

Name: ______________________
Age: ______________________

Please answer the following questions based on your previous history.

1. How many days do you wear high-heeled shoes in a week?

____

2. How many days do you wear high-heeled shoes in a month?

____

3. How long have you been wearing high-heeled shoes?

____

4. How high are your high-heeled shoes that you often wear?

____

5. What type of high-heeled shoes do you wear?

a) Stiletto

b) wedge heel

c) blocked

6. In your opinion, do you consider yourself as an experienced high-heeled wearer?
(An experienced high-heeled shoes wearer is who has no difficulty in walking and travelling while wearing high-heeled shoes and is confident wearing it.)

____

Appendix 2.

Activities Specific Balance Confidence Scale (ABC)
#1 Normal Condition

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0% 10 20 30 40 50 60 70 80 90 100%
No confidence Completely confident

"How confident are you that you will not lose your balance or become unsteady when you…"

1. …walk around the house? _______%
2. …walk up and down stairs? ______%
3. …bend over and pick up a slipper from the front of a closet floor? ____%
4. …reach for a small can off a shelf at eye level? ____%
5. …stand on your tip toes and reach for something above your head?____%
6. …stand on a chair and reach for something? ____%
7. …sweep the floor? ____%
8. …walk outside the house to a car parked in the driveway? ____%
9. …get into or out of a car? ____%
10. …walk across a parking lot to the mall? ____%
11. …walk up or down a ramp? ____%
12. …walk in a crowded mall where people rapidly walk past you? ____%
13. …are bumped into by people as you walk through the mall? ____%
14. …step onto or off of an escalator while you are holding on to a railing? ____%
15. …step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing? ____%
16. …walk outside on icy sidewalks? ____%

created by:
Powell, LE, and Myers, AM: The activities-specific balance confidence scale. J Gerontology 50 A: M28, 1995.

Activities Specific Balance Confidence Scale (ABC)

#2 High-heeled shoes Condition

(Assume you are wearing high-heeled shoes when you are performing following daily activities.)

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0%	10	20	30	40	50	60	70	80	90	100%
	No confidence							Completely confident		

"How confident are you that you will not lose your balance or become unsteady when you…"

1. …walk around the house? ______%
2. …walk up and down stairs? _____%
3. …bend over and pick up a slipper from the front of a closet floor? ____%
4. …reach for a small can off a shelf at eye level? ____%
5. …stand on your tip toes and reach for something above your head?____%
6. …stand on a chair and reach for something? ____%
7. …sweep the floor? ____%
8. …walk outside the house to a car parked in the driveway? ____%
9. …get into or out of a car? ____%
10. …walk across a parking lot to the mall? ____%
11. …walk up or down a ramp? ____%
12. …walk in a crowded mall where people rapidly walk past you? ____%
13. …are bumped into by people as you walk through the mall? ____%
14. …step onto or off of an escalator while you are holding on to a railing? ____%
15. …step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing? ____%
16. …walk outside on icy sidewalks? ____%

created by:
Powell, LE, and Myers, AM: The activities-specific balance confidence scale. J Gerontology 50 A: M28, 1995.

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