Biomechanical study with kinematic and kinetic descriptions of the effect of high-heeled shoes in healthy adult females based on gait analysis

Sadiq J. Hamandi1, Duaa M. Ruken1

1 Biomedical Engineering Department, Al-Nahrain University
sadiq_hamandi@eng.nahrainuniv.edu.iq

Abstract. Many women remain unaware of the negative effect of high-heeled shoes and the damage and significant changes they can cause in the human body. Studying the effect of high heels during walking shows biomechanical changes in the person wearing the shoes based on their influence on ankle joints, foot pressure distribution, and muscle activity, and changes in Ground Reaction Forces. This study examined the effects of high heels and smooth-soled court shoes using gait analysis. Experiments were conducted on five healthy volunteers, who were all young women without known diseases or muscle or bone injuries; most were also accustomed to wearing high heels on a daily basis. The volunteers' average age was 22.4 years, the average height 160 cm, and the average weight 59.8 kg. Three types of high heels were used; each volunteer was thus required to walk barefoot, with 1 cm heels, 5 cm heels, and with 7cm heels. The result showed that the step length and ankle joint angle decreased as the heel height increased, causing the speed of gait to become slower and the cadence to increase, thus increasing vertical ground reaction force and the moment of the knee joint. Women should be advised not to wear shows with heel heights greater than 5 cm to reduce the injury risk and preserve comfort.

1. Introduction
The human gait is a complex spatiotemporal process involving multiple structures and functions of the neuromusculoskeletal system. Gait analysis is a branch of biomechanics that is concerned with the study of locomotion from a mechanical perspective, and thus analysis of the human gait involves the cooperation of specialists from both medical and engineering sciences [1]. Wearing high-heeled shoes has become a regular feature for women in multiple forums, including work and social applications. For some women, wearing high-heeled shoes enhances their confidence, while others are subject to social expectations or employment requirements. Some women thus wear high-heeled shoes for more than seven hours each day while performing daily activities such as walking and standing [2]. Maintaining balance is particularly complicated during the walking process due to the pattern of movement of the lower limbs. Wearing footwear constrains the natural foot motion, potentially decreasing walking stability further. High-heeled shoes in particular force the foot into plantar flexion, leading to instability in the gait. The altered anatomical position of foot results in compensatory mechanical changes to maintain equilibrium, and these alterations in walking kinematics and kinetics may contribute to a variety of complications, such as muscle overuse, strain injuries, joint degeneration, increased risk of falling, and back and foot pain [3]. Jing and Soul (2012) [4] examined the effects of walking in fifteen young females wearing high heeled shoes and carrying asymmetrical loads, with a focus on their lower extremity joints. They studied the moments of the ankle, knee, and hip in the frontal and sagittal planes for women in flat, 30 mm, and 90 mm height heels carrying loads of 5 and 10 kgs. The results showed that as the heel height increased, the extensor moment of the hip increased notably. Maduabuchi et al. (2012) [5] determined the parameters of gait for different heel heights for a sample of young Nigerian females of average age, weight, and height of 22 years, 60 kg, and 165 cm,
respectively. An ex post facto design was applied to examine different heel height effects (32 mm, 78 mm, and 110 mm) on gait parameters. Loredo et al. (2015) [3], presented a comparative study on movement of the lower limbs during different phases of gait while wearing low heeled and high heeled shoes in young adult athletes such as runners. In terms of gait in high heeled shoes, step length and joint ankle range of motion decreased, causing slower gait speeds and higher cadence. Slawomir et al. (2017) [6], examined the effects of long term gait in high heeled shoes on foot movements during barefoot walking. The results showed that walking in high heeled shoes altered barefoot foot techniques, displayed in the form of shorter duration through 4% of the 1st and 2nd rocker and a notably longer duration through 5% of the 3rd rocker phase, with a considerable dropping in the transverse foot arch height of up to 50% in women who usually wore high heeled shoes. Kuan et al. (2017) [2] performed gait analysis for twelve subjects; the results showed that increasing heel height led to increased cadence and vertical ground-reaction force compared with barefoot walking, decreasing stride length and step length. A woman wearing high heels sends a variety of messages about her chosen sexual role, sexuality, confidence, and power [7].

Specific features for healthy shoes include
1. a rounded toe with enough depth to prevent calluses;
2. good arch support;
3. Achilles tendon protector to reduces stress on the Achilles tendon by locking the shoe around the heel;
4. heel collar to cushion the ankle and ensure a proper fit;
5. upper to hold the shoe on the foot, whether made of leather, mesh, or synthetic material. Mesh allows better ventilation and is lighter weight;
6. insole to cushion and supports the foot and arch; removable insoles can be laundered or dried between walking sessions;
7. gel, foam or air midsole to cushion and reduce impact when the foot strikes the ground; and
8. outsole to make contact with the ground and protect the sole; grooves and treads can help maintain traction.

2. Clinical Gait Cycle
A stride of a gait cycle for one leg may be clarified as being the sequence and time of movement between one gait event, normally foot contact, and that event’s recurrence in the same leg. Generally, the cycle of gait is classified as five stance-phase intervals and three swing phase intervals, as shown in Figure 1 [8].

![Figure 1](image) Events, periods, and phases of the right leg gait cycle [8].
2.1 Calculation of Segment and Joint Angles

Converting the marker trajectories into segment angles is done using the trigonometric tangent function as shown in Fig. 2:

\[
\tan \theta = \frac{(y_d - y_p)}{(x_d - x_p)}
\]

(1)

Ankle joint, knee joint, and hip joint angles are calculated in this manner. Based on the normal anatomical position, the angle joint should be modified for clinical agreement by subtracting 90º for the ankle [12].

![Figure (2) Segment angles calculated using trigonometry; angles of the joint may be determined from the difference of angles between adjacent segments [12].](image)

2.2 Kinetic Concepts of Lower limbs

Kinetic quantities are calculated using Newton’s second law of motion, which incorporates inertia vectors as seen in Figure 3. All moments are taken about the centre of mass of each segment, with positive forces assumed to be in the upward direction and positive moments in the counter clockwise direction. As the default sampling rates of the camera and force plates were 25 and 50 Hz, respectively, down sampling was performed using the MATLAB command "resample".

![Figure (3) Free body diagrams of the lower extremity segments (foot and shank) demonstrating segment forces.](image)

3. Ground Reaction Forces

The ground reaction forces (GRFs) are the major external forces applied on the feet by the ground. In clinical analysis, the force of ground reactions is decomposed into three perpendicular components as shown in Figure 4. These are [13]

1. The vertical component, \( F_z \).
2. The forward backward component, \( F_y \).
3. The medial lateral component, \( F_x \).
The vertical component, $F_z$, supports the body weight and the horizontal components, $F_x$ and $F_y$, represent the force of ground friction. The forces are usually determined as a percentage of body weight $BW$ [13].

![Figure 4](image)

**Figure 4** Force plate data obtained from a normal individual walking at normal speed plotted against time as a percentage of the stance phase.

A. Vertical forces, B. Anterior-posterior forces, C. Medial-lateral forces [13].

### 4. Experimental work

Five female volunteers aged from 20 to 24 years collaborated in this study (Table 1). The recruitment criteria were capability of walking on a 6-metre walkway in high heels shoes of different heights, and no indication of acute or chronic diseases or joint osteoarthritis of the lower extremities or malleability in neuro-musculoskeletal system.

**Table 1** Volunteers’ ages, sex, weight in kilograms, height in metres.

| Volunteers number | Age | Sex  | Weight (kg) | Height (metres) |
|-------------------|-----|------|-------------|-----------------|
| 1                 | 23  | Female | 61          | 1.60            |
| 2                 | 24  | Female | 60          | 1.57            |
| 3                 | 22  | Female | 60          | 1.61            |
| 4                 | 20  | Female | 58          | 1.58            |
| 5                 | 23  | Female | 60          | 1.62            |

Kinetics and kinematic data can be determined using gait analysis arrangements. For the duration of the experiment, the volunteers wore close-fitting clothing to guarantee the precision of the tests and to reduce inaccuracy in the marker recognition due to skin-movement and vibrations of the muscles during walking. After each trial, every volunteer completed a questionnaire, and four passive markers were placed at anatomical landmarks on the joints of the lower legs. The volunteers were then each asked to carry out several walking experiments on a 6-metre wooden walkway, going barefooted and then in 1 cm, 5 cm and 7 cm heels at self-selected speeds. The volunteers were asked to make as many trials as required to become comfortable and to walk as normally as possible. Finally, ten walking experiments were selected for each volunteer for data-processing.
5. Gait Analysis System Overview

The gait analysis laboratory used is sited at the department of Biomedical-Engineering of Al Nahrain University. It has two AMTI force platforms (498 × 498 × 44 mm) with an attached computer unit and two dimensional (2D) motion analysis system, as seen in Figure 5. After kinematic and kinetic collection of data, analysis was carried using MATLAB software (R2011a) after processing and filtering stages.

![Figure 5 Gait analysis laboratory](image)

6. Measurements of the General Gait Parameters

Temporal factors and distance as related to gait analysis represent gait-parameters including walking speed, stride frequency, and stride length. The measurement of general gait parameters can be achieved in several ways, and the basic consideration of gait is offered by the indicated factors. The procedure followed gives the three gait parameters based on watching the volunteers’ recorded gaits. The Kenova application was used to measure time and distance. The number of procedures in a given interval was computed as in Figure 6, and given the time interval and the number of procedures, the gait parameters were calculated using the equations below [10]:

\[
\text{Speed (metres per second)} = \frac{\text{Distance (metres)}}{\text{time (second)}} \quad (2) \\
\text{Stride length (metres)} = \text{distance (metres)} \times \left(\frac{2}{\text{steps counted}}\right) \quad (3) \\
\text{Cadence (steps/minutes)} = \text{steps counted} \times \left(\frac{60}{\text{time (seconds)}}\right) \quad (4)
\]

![Figure 6 Schematic top view of the walkway, illustrating the variables used for calculating general gait parameters](image)
6.

Figure 7 Schematic flow chart describing kinematics and kinetics analysis.

7. Kinematic Parameters Measurement During Gait Cycle

The 2-dimensional gait-analysis system offered measurements of kinematic variables representing the position, angles, and orientation of the lower leg joints. The situation of markers on anatomical references allowed the location and activity of the joints to be precisely ascertained, and by tracking with video-motion Skillspector software, these locations were transformed into movement data. The camera had a frame rate of twenty-five frames/second offering a suitable resolution of time. The camera was placed 2.8 meters away from the walkway at a 90º angle to the motion plane at a height of 80 cm above the ground. Multiple 2D measurements were thus obtained.

7.1 Marker Placement

A group of four markers, circular stickers with radii of 12 mm, was set at tangible anatomical landmarks. The markers thus approximated the centres of rotation for the various segments being analysed. Table 2 shows the positions for each marker on the legs [13], and the position of markers for the walking test is shown in Figure 8.

To define the major trochanter precisely, the volunteer was called to stand upright, flexing her knees and rotates her femur medially and laterally.

Table 2 Approximate locations of the markers [13].

| Marker | Marked Location          | Position      |
|--------|--------------------------|---------------|
| 1      | Greater Trochanter       | Right hip     |
| 2      | Lateral femoral epicondyle | Right knee   |
| 3      | Lateral malleolus        | Right ankle   |
| 4      | Fifth metatarsal head    | Right forefoot|
7.2 Marker Digitization Process
The Skillspector program was used to simplify the model of the lower leg. The model was formed of three body segments including four body positions: the hip, knee, ankle, and 5th metatarsal head of the right foot. The digitising profile was selected according to which leg made contact with the force plate, and the digitized points were made available for import to MATLAB by being stored in a .txt format [15]. The marker digitising step is shown in Figure 9.

The digitising markers' positional accuracy can also be changed to upgrade the intensity of the images [15]. Figure 10 shows four subjects in each case after the digitisation process. The Skillspector works on an AVI video format; other video formats must be transformed to an AVI format using video converting programs or online convertors prior to use [15].

Figure 8 The locations of markers on a subject's body.

Figure 9 Skillspector program operation: 1) Digitisation mode selection; 2) marker position selection; 3) next frame selection; and 4) digitised point extraction.
8. Kinetic Parameters’ Measurement During Gait Cycle
A force plate was used to measure the ground reaction force as the subject walked across it. It was important that the volunteers walked on the force plates as part of the natural condition during the course of moving along the walkway, so the force plates were mounted on a 6,000×1,220×106 mm flat wooden walkway. Two force plates with different dimensions were available in the laboratory, so the force plate with dimensions 498×498×440 mm was put on a wooden platform of 62 mm height inside the walkway [16]. Figure 11 shows the dimensions of the force plates.

![Figure 11 Force plate dimensions [15].](image)

Each platform has six transducers that measure input length on the upper surface in all three axes when force is applied. The electrical output of the platform thus consists of

1. $F_x$, $F_y$, $F_z$, the values of the force vector
2. $M_x$, $M_y$, $M_z$, the three moments of force constructed from the platform centre

To obtain precise data, the foot must completely contact the plate while the other foot remains clear of the plate throughout the stride. This required repeating the test several times before the proper foot contact pattern was developed [16].

9. Results and Discussion
The general gait parameter results included step length, walking speed, stride length and cadence. The stride length, cadence, step length and walking speed for barefoot, 1cm heel, 5cm heel, and 7cm heel cases for the five subjects are shown in Table 3.

Table 3 Mean and SD of general gait parameter for the five subjects.

| General gait parameter | Bare-foot (mean ±SD) | 1cm heel (mean± SD) | 5 cm heel (mean± SD) | 7 cm heel (mean ±SD) |
|------------------------|----------------------|---------------------|----------------------|----------------------|
| Cadence (step/min)     | 98.403±2.492         | 100.09±2.230        | 105.218±1.133        | 109.915±1.09         |
| Step length (m)        | 0.657±0.049          | 0.648±0.062         | 0.609±0.054          | 0.567±0.065          |
| Walking speed (m/s)    | 1.084±0.0655         | 1.034±0.0653        | 0.992±0.063          | 0.960±0.025          |
| Stride length (m)      | 1.315±0.0995         | 1.297±0.124         | 1.219±0.109          | 1.134±0.1312         |

The results showed that as the heel height increased, the subjects demonstrated shorter stride length and step length, leading to higher cadence and slower gait speed. This may imply a more careful walking pattern to neutralize the elevation and forward shift of the centre of gravity and changed biomechanics of the foot imposed by higher heels in order to prevent falls and foster postural stability. A considerable difference in all selected gait parameters across the different heights was observed. This essential alteration in the kinematics of the ankle and the knee involved placing the foot in a more plantar-flexed position at the initiation of support, and the increase in the centre of gravity as the heel height increased shifted the centre of mass forward, resulting in postural instability. The results suggested that decrease in walking speed was due to the fact that the subjects simply could not walk at the same speed in high-heels; the subjects also felt more comfortable at a lower speed when wearing high-heels, most likely linked to safety, as the risk of falls increases where subjects cannot follow the same rhythm as in normal walking.

9.1 Force of Vertical Ground Reaction

The ground reaction forces’ components for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 12 for the vertical component. Acceleration of the centre of gravity causes the first peak of the vertical force of ground reaction through stance and deceleration creates the second peak during downward movement, which can be examined through the next stance. The forces of ground reaction were expressed as a percentage of the time of stance. The foot is removed from the force plate in the swing phase, and the force of ground reaction is thus zero at that point.
The results showed a slight change in values of VGRF (increase and decrease) on wearing high heels, and the second peak was increased and more stable than the first peak as though the volunteer did not feel comfortable at first (initial contact) and needed to depend on one limb to ensure the stability of the other limb, as seen in Table 4.

### Table 4 Mean and SD of vertical ground reaction force for the five subjects.

| Heel Heights | Maximum VGR (Fz1) (mean ±SD) | Maximum VGR (Fz2) (mean ±SD) | Minimum VGR (Fz min) (mean ±SD) |
|--------------|------------------------------|-----------------------------|--------------------------------|
| Bare-foot    | 1.03±0.04                    | 1.08±0.03                   | 0.77±0.03                      |
| 1cm heel     | 1.05 ±0.05                   | 1.12±0.04                   | 0.80±0.03                      |
| 5 cm heel    | 1.06±0.051                   | 1.14±0.03                   | 0.801±0.02                     |
| 7 cm heel    | 1.08±0.04                    | 1.14±0.04                   | 0.83±0.03                      |

9.2 Ankle Moment

The sagittal plane joint moments for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 13 for ankle joints.

The moment of the ankle joint at initial contact is dorsiflexion and the dorsiflexion muscles perform eccentrically to depress the foot into the ground. The plantar flexors increase their activity through the mid and final stance, concentrically contracting to improve the leg’s movement into the swing, in which the moment of the ankle joint rapidly approaches zero. The tibia moves forward in mid-stance over the foot, and the moment of the ankle joint becomes progressively plantar flexor.

Wearing high heels forces the feet into more plantar flexion. The results showed that the peak of ankle plantar flexion moment was reduced as heel height increased due to the increase in plantar flexion caused by wearing high heels during walking. This can be demonstrated by the shorter triceps-surae-fascicle lengths and the smaller moment arm of the Achilles tendon, combined with a ground reaction force vector that is nearer to the centre of the ankle joint to decrease the moment requirement. However, the force of Achilles tendon actually increases due increases in the activity of the calf-muscle with increases in heel-height. In any case, the smaller plantar flexor moment in the sagittal plane observed on walking in high-heels is slightly recovered by increasing the knee extensor moment amplitude. Smaller plantar flexor moments may also mean greater dependence on proximal leg muscles, such as the quadriceps, to obtain leg propulsion when walking in high heels. The results also showed slightly increases in the peak of ankle dorsiflexor moment.
9.3 Knee moment
The sagittal plane joint moments for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 14 for the knee joint.

![Figure 14 Knee moment for the four cases.](image)

In general, when the foot contacts the ground in a high-heeled shoe, the knee is more flexed; this remains the case during the rest of the stance phase, and the amount of knee flexion appears to increase with increasing heel height. Accordingly, the results showed that the peak of knee extensor moment increased as heel height increased.

The results also showed that walking in high heels increases the peak moment of knee extensor. Other reported effects of high-heels at the knee include a larger range of motion during the stance phase and decreased flexion during the swing phase. The reported increase in knee-flexion during stance occur simultaneously with increased quadriceps muscle electromyography (EMG). This might permit better attenuation of impact forces and slightly compensate for the loss of ankle dorsiflexion in high heels. However, the changes also prolong patellofemoral joint pressure and patella tendon strain, and thus increase the tibiofemoral compressive forces, likely contributing to knee pain and degenerative joint changes. Wearing high heels thus contributes to the knee osteoarthritis. The results also showed slightly decreases in the peak of knee flexor moment.

9.4 Hip Moment
The sagittal plane joint moments for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 15 for the hip joint.

For the hip joint, during the initial loading of support phase, there is a net moment of hip extensor that continues through mid-stance. In late stance, while hip extension is decelerated through the hip flexors there is an absorption of net power. The hip muscle flexors become shorter, producing power for the initiation of the swing phase and pulling the thigh upward and forward in preparation for toe-off. Hip flexion continued at swing through the production of power and flexor muscle moment until terminated in the back swing by the hip extensor moment.
The results showed that as heel height increased, there was a brief rise in the peak of the moment of the hip flexor in the first stance segment. Hip flexion was partially decreased in the swing phase, and there was a partially decrease in the peak moment of hip extensor. It appears that if biomechanical differences at the hip are present between walking in high heels and flat shoes, they are small in general, especially compared to the changes seen at the ankle and the knee, as seen in Table 5.

Table 5 Mean and SD of the kinetic data for the five subjects.

| Kinetic data                      | Bare-foot (mean ±SD) | 1 cm heel (mean ±SD) | 5 cm heel (mean ±SD) | 7 cm heel (mean ±SD) |
|-----------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Maximum Hip Extensor Moment (N.m)| 0.20±0.09             | 0.30±0.21             | 0.41±0.10             | 0.52 ± 0.14          |
| Maximum Hip Flexor Moment (N.m)  | -1.04±0.22            | -1.07 ± 0.26          | -1.09±0.27            | -1.11 ± 0.29         |
| Maximum Knee Extensor Moment (N.m)| 0.18±0.07             | 0.19±0.21             | 0.21±0.06             | 0.27±0.23            |
| Maximum Knee Flexor Moment (N.m) | -1.11±0.29            | -1.09±0.28            | -1.08±0.27            | -1.07±0.26           |
| Maximum Ankle Plantarflexor Moment (N.m) | 1.14±0.08             | 1.32±0.11             | 1.56 ± 0.13           | 1.34 ± 0.20          |
| Maximum Ankle Dorsiflexor Moment (N.m) | -0.108±0.04            | -0.11 ± 0.07          | -0.14±0.09            | -0.16 ± 0.10         |

9.5 Ankle Angle
The sagittal plane angular displacement for barefoot, 1 cm, 5 cm, and 7 cm cases for the ankle joint are shown in Figure 16. The ankle joint is normally plantar flexed at heel strike and dorsiflexed in stance then plantar-flexed at toe off. During the swing phase, 62 to 100% of cycle of gait, the ankle continues into dorsiflexion. According to the calculation protocol, positive ankle angles signify dorsiflexion while negative angles
signify plantar flexion; thus, an increase in plantar flexion results in a greater negative ankle angle and an increase in dorsiflexion results in a greater positive angle.

![Figure 16 Ankle angle for the four cases.](image)

The results showed that maximum plantar flexion angle increased negatively as a function of heel height, as the foot was placed in a more plantar-flexed position as heel height increased. Analysis of the maximum dorsiflexion parameter also revealed that the ankle became less dorsiflexed as heel height increased. In high heels, the ankle never attained a full dorsiflexed position.

9.6 Knee Angle
The sagittal plane angular displacements for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 17 for the knee joint. Generally, the knee joint was flexed in stance phase from 0 to 62% of the gait cycle to absorb body weight. At mid-stance, maximum knee flexion occurred, while at the terminal stance, 35 to 55% of the gait cycle, the knee joint was extended. During the swing phase, 62 to 100% of the gait cycle, at mid swing, the knee joint was flexed, reaching a maximum flexion.

![Figure 17 Knee angle for the four cases.](image)

The results showed that as the heel height increased, the knee flexion angle increased. Maximum knee flexion increased as a function of increasing heel height, resulting in the knee being placed in a more flexed position as the heel height increased; full knee extension was not reached in heels.
9.7 Hip Angle
The sagittal plane angular displacements for barefoot, 1 cm, 5 cm, and 7 cm cases are shown in Figure 18 for the hip joint.

The hip joint was flexed, absorbing the weight of the body in stance-phase for the period 0 to 62% of the gait cycle. At 35 to 55% of the gait cycle, the hip joint was extended. The hip joint was flexed to reach a maximum at mid-swing, during swing phase, in the final 62 to 100% of the gait cycle.

The result showed that as heel height increased there were no significant differences in hip flexion angle and hip extension angle, as seen in Table 6.

| Kinematic data                               | Bare-foot  | 1 cm heel | 5 cm heel | 7 cm heel |
|---------------------------------------------|------------|-----------|-----------|-----------|
| Maximum Hip Extension Angle (°)             | -7.5±5.3   | -8.6±6.2  | -8.5±5.9  | -8.3±5.4  |
| Maximum Hip Flexion Angle (°)               | 22.2±7.5   | 21.3±6.2  | 21.0±6.3  | 21.8±5.9  |
| Maximum Knee Extension Angle (°)            | 9.8±4.3    | 10.3±4.5  | 10.1±4.2  | 10.2±4.1  |
| Maximum Knee Flexion Angle (°)              | 21.1±6.0   | 22.6±6.9  | 23.2±7.4  | 24.9±7.1  |
| Maximum Ankle Dorsiflexion Angle (°)        | 3.6±3.5    | -3.9±3.9  | -4.3±3.6  | -5.1±4.1  |
| Maximum Ankle Plantarflexion Angle (°)      | -10.1±3.9  | -15.3±3.1 | -25.6±3.3 | -34.5±3.1 |

10. Conclusions
1. Certain specific gait parameters such as step length and stride length were shortened as heel height increased, producing a slower gait speed and higher cadence.
2. As heel height increased, there was a slight change in values of VGRF (increase and decrease); the second peak was larger and more stable than the first peak.
3. As heel height increases, the knee and ankle undergo marked changes in joint kinetics as they are be modified to match the exaggerated plantar-flexure posture.
4. The orientation of lower extremity segments was changed on wearing high heeled shoes, with particular changes at the knee and ankle.
5. Wearing high heeled shoes changes the orientation of the lower extremity segments, with the most obvious changes occurring at the ankle and knee. The data indicate that heel heights above 5 cm can greatly influence lower extremity mechanics, which may in turn affect the energy cost of gait. Walking in high heels is an unnatural activity that alters the angular patterns of the ankle and knee, and as a result of these changes, the centre of mass is raised and shifted forward, increasing vertical loading. However, the kinematic changes preclude attenuating this vertical loading as balance becomes an important factor at higher heel heights. To maintain comfort and reduce the risk of injury, women should thus be advised not to wear shoes with a heel height greater than 5 cm.

References:

[1] Winter, D.A., Sandra J. Olney, Jill Conrad, “Adaptability of motor patterns in pathological gait”, Springer New York, ISBN: 978-1-4613-9030-5, 1990.
[2] Kuan Y., Chew Yin Q., Tan Siow Ch., Chan, “The effects of different high heeled shoes during gait at the kinetic and kinematic impact”, Selangor, Malaysia, IEEE: 978-1-5386-2126-4, 2017.
[3] Jacob B. Loredo, Mauricio B. J. Aguirre, Erwing J. L. Ruano, “Influence of high heels on walking motion: gait analysis”, México, ITESM, 2015.
[4] Jing X. Li and Soul Lee, “Joint moment of lower limbs during walking with high heeled shoes and asymmetric load carrying in young females”, Ottawa, Canada, 2012.
[5] Maduabuchi J. N., Afamefuna V. E., Antoninus O. E., Chidubem K. N., “Effects of different heel heights on selected gait parameters of young undergraduate females”, Nigeria, Vol.3, No.3 ISSN: 2008-4978, 2012.
[6] Slawomir W., Alicja R., Pawel Z., Natalia U., Sebastian K., “Foot mechanics in young women are altered after walking in high heeled shoes”, Poland, Vol.19, No. 3, DOI: 10.5277/ABB-00671-2016-04, 2017.
[7] M. Zhang and Y. Fan, “Computational biomechanics of the musculoskeletal System”, pp. 21, 2015.
[8] C. L. Vaughan, B. L. Davis and J. C. O’Connor, “Dynamics of human gait”, Human Kinetics Publishers, 1999.
[9] C. Kirtley, “Clinical gait analysis: Theory and Practice”, Elsevier, 2003.
[10] M. W. Whittle, “Gait analysis: an introduction”, Elsevier, 2002.
[11] I. W. Griffiths, “Principles of biomechanics and motion Analysis”, International journal of Sports Science and Coaching, vol.1. Lippincott Williams & Wilkins, pp. 421–423, 2009.
[12] Chris Kirtley, “Clinical gait analysis: theory and practice”, ISBN: 0 4431 0009 8, 2004.
[13] B. A. Faihan, “Dynamic Analysis of Human Gait Cycle”, master thesis, Al-Nahrain University, Baghdad, Iraq, 2013.
[14] V. Racic, A. Pavic and J. M. W. Brownjohn, “Experimental identification and analytical modelling of human walking forces: literature review”, Journal of Sound and Vibration, vol.326, no.1–2, pp.1–49, Sep-2009.
[15] M. M. Ghazi, “The effect of body mass index on human gait analysis”, master thesis, Al-Nahrain University, Baghdad, Iraq, 2018.
[16] M. F. Jameel, “Gait analysis after unilateral total hip replacement surgery”, master thesis, Al-Nahrain University, Baghdad, Iraq, 2015.