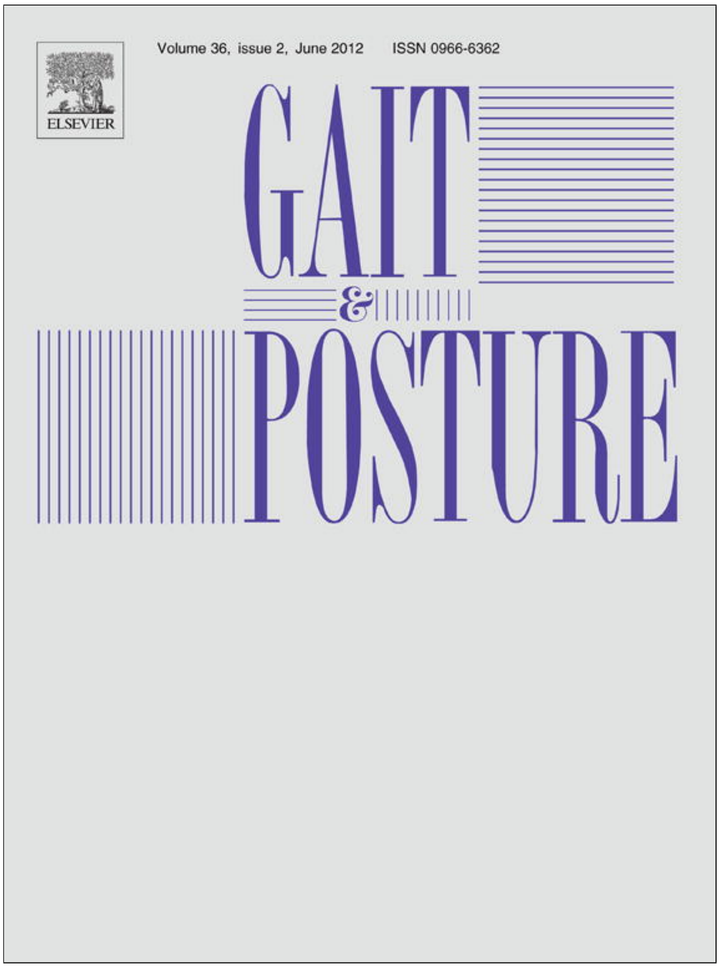
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The influence of heel height on patellofemoral joint kinetics during walking

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ABSTRACT

Although wearing high-heeled shoes has long been considered a risk factor for the development for patellofemoral pain (PFP) in women, patellofemoral joint kinetics during high-heeled gait has not been examined. The purpose of this study was to determine if heel height increases patellofemoral joint loading during walking. Eleven healthy women (mean age 25.0 ± 3.1 yrs) participated. Lower extremity kinematics and kinetics were obtained under 3 different shoe conditions: low heel (1.27 cm), medium heel (6.35 cm), and high heel (9.53 cm). Patellofemoral joint stress was estimated using a previously described biomechanical model. Model outputs included patellofemoral joint reaction force, patellofemoral joint stress and utilized contact area as a function of the gait cycle. One-way ANOVAs with repeated measures were used to compare the model outputs and knee joint angles among the 3 shoe conditions. Peak patellofemoral joint stress was found to increase significantly ($p = 0.002$) with increasing heel height (low heel: 1.9 ± 0.7 MPa, medium heel: 2.6 ± 1.2 MPa, and high heel: 3.6 ± 1.5 MPa). The increased patellofemoral joint stress was mainly driven by an increase in joint reaction force owing to higher knee extensor moments and knee flexion angles. Our findings support the premise that wearing high-heeled shoes may be a contributing factor with respect to the development of PFP.

1. Introduction

Patellofemoral pain (PFP) is one of the most common disorders of the lower extremity, accounting for 25% of all knee injuries treated in orthopedic clinics [1,2]. In addition, PFP has been shown to be more common in women compared to men [3]. It has been proposed that PFP may be the result of increased patellofemoral joint stress, which is defined as the patellofemoral joint reaction force per unit area of contact of the patella against the femur [4].

Wearing high-heeled shoes has long been considered a potential risk factor for the development for PFP in women [3]. Previous studies have shown that high-heeled gait increases the knee flexion angle during the loading phase of gait [5], which could lead to an elevated knee extensor moment and patellofemoral joint reaction force. Saunders et al. [5] suggest that exaggerated knee flexion is needed during loading response to compensate for the loss of ankle dorsiflexion caused by the wearing of high-heeled shoes.

Apart from the patellofemoral joint reaction force, patellofemoral joint contact area also has been shown to vary with the knee flexion angle. Powers and colleagues [6] have reported that patellofemoral joint contact area increases linearly from 0 to 30 degrees of knee flexion, remains unchanged from 30 to 60 degrees, and decreases slightly from 60 to 90 degrees of knee flexion. Therefore, greater knee flexion angles during loading response while wearing high-heeled shoes may result in greater contact area, and potentially offset any increase in patellofemoral joint reaction force. However, Goudakos et al. [7] have reported that the regulatory influence of increasing contact area to protect against high patellofemoral pressure is exhausted at relatively low loads. Therefore, an elevated patellofemoral joint reaction force has been suggested to be the key determinant with respect to the increased patellofemoral joint stress [7].

To date, a thorough understanding of how high-heeled gait influences patellofemoral joint kinetics is lacking. Using a previously described patellofemoral joint model, the purpose of this study was to determine if heel height increases patellofemoral joint stress during walking. A secondary purpose was to identify the kinematic and kinetic variables that may explain patellofemoral joint stress differences when wearing shoes with varied heel heights.

2. Methods

2.1. Subjects

Eleven healthy, pain-free women participated in this study. The average age, height and weight of the study participants were 25.0 yrs (SD 3.1), 161.6 cm (SD 5.4), and 55.5 kg (SD 7.1), respectively. Participants who reported any current orthopedic injury or medical condition that prevented normal ambulation were excluded from participation. All subjects had prior experience wearing high-heeled

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shoes and were current casual wearers. On average, subjects reported wearing high heels 5.0 times a month (SD 2.3). Prior to testing, each subject signed a consent form approved by the Institutional Review Board of the University of Southern California.

2.2. Instrumentation

Walking trials were conducted along a 10 m walkway with the middle 7 m designated for data collection. Each subject's walking velocity was monitored via photoelectric triggers placed at both ends of the walkway. Ground reaction forces were collected at a rate of 1560 Hz using an AMTI force plate (Model #OR6-6-1000, Advanced Mechanical Technology Inc., Watertown, MA). The force plate was covered with high pressure laminate (similar to the rest of the laboratory floor). An 8 camera motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data at 120 Hz. To quantify lower extremity kinematics, reflective markers (14-mm spheres) were placed on specific anatomical landmarks (see below for details).

Three types of women's fashion shoes that varied in heel height (low: 1.27 cm, medium: 6.35 cm, and high: 9.53 cm) were evaluated in this study (Fig. 1). Each pair of shoes was from the same manufacturer (Bandolino, Jones Apparel Group, New York City, NY) and was chosen for its similarities in design, construction, and material.

2.3. Procedures

All testing was performed at the Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. To allow for accurate placement of reflective markers, subjects wore sport shirts and shorts. Subjects were also provided with footwear in their respective size and completed 2 practice trials for each heel height condition to check for proper shoe fit and comfort. Reflective markers were then placed on the following anatomical landmarks: the 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, the joint space between L5–S1 and bilaterally over the greater trochanters, iliac crests and anterior superior iliac spines (ASIS). The foot markers were placed on the shoes and all other markers were attached directly on the skin. In addition, clusters of rigid reflective tracking markers were placed on the lateral surfaces of each subject's thigh, lower leg, and heel counter of the shoe. After obtaining a static calibration trial, all anatomical markers (with the exception of those attached to the pelvis) were removed.

In total, subjects completed 9 walking trials (3 trials per shoe condition). As high-heeled gait has been shown to be more energy consuming than low-heeled gait [8,9], the low heel shoe was tested first and followed by the medium and high heel shoes. This was done to mitigate any potential effects due to fatigue. Furthermore, a 10 min rest period was provided between the 3 shoe trials.

A trial was deemed acceptable based on 2 criteria. First, the subject's dominant foot (i.e., foot used to kick a ball) had to strike within the boundaries of the force plate. Second, the subject's walking velocity had to be within $\pm$ 5% of each subject's self-selected velocity during the first trial of the low heel condition. The average walking velocities during the low heel, medium heel, and high heel conditions were 82.9 m/min (SD 10.5), 82.8 m/min (SD 10.7), and 83.2 m/min (SD 10.4), respectively.

2.4. Data analysis

Reflective markers were labeled and digitized using Vicon 612 software (Oxford Metric Ltd., Oxford, UK). Visual 3D software (C-Motion, Rockville, MD) was used to quantify sagittal plane joint motions of the knee joint. Kinematic data were filtered using a 4th order, 6 Hz, low pass Butterworth filter with zero lag compensation. An inverse dynamics approach, utilizing unfiltered ground reaction forces, was used to determine the net knee joint moment.

A previously described patellofemoral joint model was used to quantify joint stress [4,10,11]. An overview of the model is illustrated in Fig. 2. Input variables for the model algorithm included knee joint flexion angle, net knee joint moment, and patellofemoral joint contact area as reported by Powers et al. [6]. The first step of the algorithm was to approximate the quadriceps force [4,11]. The effective lever arm for the quadriceps was determined for the continuous knee joint angle position by using an equation developed by van Eijden et al. [12]. Next, the knee extensor moment at each knee flexion angle was divided by the corresponding lever arm, to obtain quadriceps force.

The second step of the algorithm was to estimate the patellofemoral joint reaction force [4,11]. van Eijden and colleagues [13] have reported that the ratio between patellofemoral joint reaction force and quadriceps force is a function of knee flexion angle. This ratio was described as a coefficient and an equation was fit to the data so that it could be obtained as a function of knee flexion angle. For each knee flexion angle, the coefficient was then estimated from the curve. This coefficient was then multiplied by the quadriceps force to obtain the patellofemoral joint reaction force.

The patellofemoral joint contact area was estimated based on the data of Powers et al. [6]. More specifically, 7 discrete contact areas (83, 140, 227, 236, 235, 211, and 199 mm^2) as reported for 7 knee flexion angles (0, 15, 30, 45, 60, 75, and 90 degrees) were used to obtain the continuous contact areas from 0 degrees to 90 degrees of knee flexion using a second order polynomial curve fitting algorithm. Patellofemoral joint stress was then obtained by dividing the patellofemoral joint reaction force by the utilized contact area for the knee flexion angle corresponding to the patellofemoral joint reaction force value.

2.5. Statistical analysis

The primary variable of interest was the peak patellofemoral joint stress. Secondary variables of interest included the following at the time of peak stress: patellofemoral joint reaction force, utilized contact area, knee extensor moment, and knee flexion angle. Separate one-way ANOVA's with repeated measures were performed to assess differences in each of the variables of interest among the 3 heel heights. For all ANOVA tests, post hoc comparisons consisting of paired t-tests were employed using a Bonferroni adjustment. As a result, the significant threshold for post hoc testing was reduced to $p < 0.016$. Statistical analysis was performed with use of SPSS statistical software (SPSS, Chicago, Illinois).

3. Results

3.1. Patellofemoral joint stress

Across the 3 heel height conditions, the peak patellofemoral joint stress occurred at the end of loading response (i.e., approximately 20% of stance phase; Fig. 3). The ANOVA comparing peak patellofemoral joint stress among the 3 shoe conditions was significant ($p = 0.002$; Table 1). Post hoc testing revealed the peak patellofemoral joint stress during the high heel condition) was significantly greater than both the medium heel ($p = 0.000$) and low heel ($p = 0.001$) conditions. Additionally, the peak patellofemoral joint stress during the medium heel condition was significantly greater than the low heel condition ($p = 0.013$).

3.2. Patellofemoral joint reaction force

The ANOVA comparing patellofemoral joint reaction force at the time of peak stress among the 3 shoe conditions was significant ($p = 0.001$; Table 1). During the high heel condition, patellofemoral joint reaction force at the time of peak stress was significantly greater when compared to medium heel ($p = 0.000$) and low heel

Fig. 1. The three shoe designs used in this study: low heel (left: 1.27 cm), medium heel (center: 6.35 cm) and high heel (right: 9.53 cm).

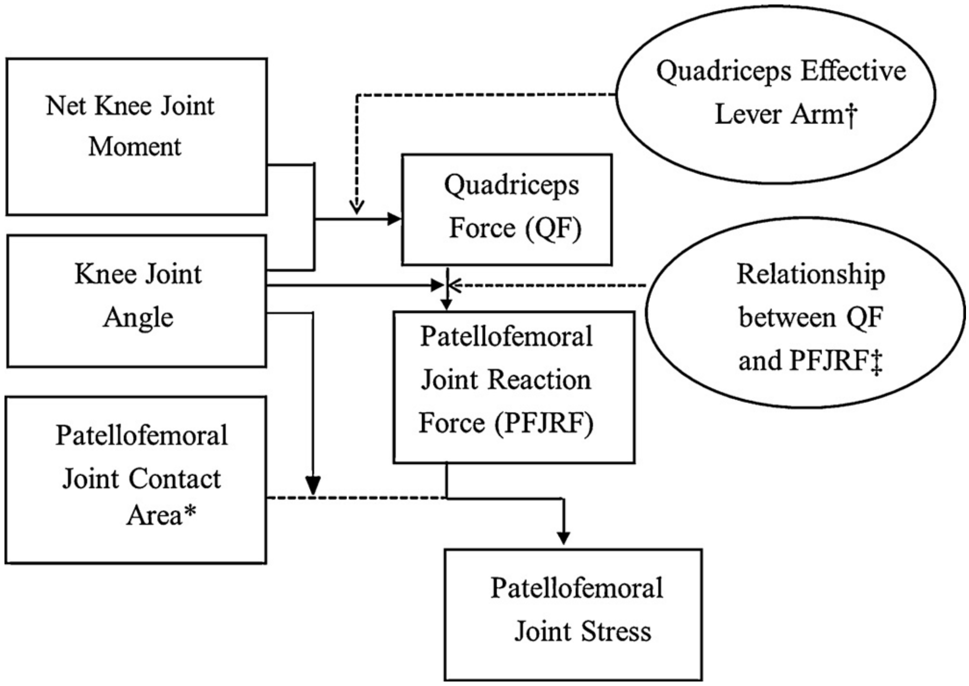

Fig. 2. Flowchart of patellofemoral joint model. *Data obtained from Powers et al. [6] †Data obtained from van Eijden et al. [12] ‡Data obtained from van Eijden et al. [13].

($p = 0.001$) conditions. Additionally, patellofemoral joint reaction force at the time of peak stress during medium heel condition was significantly greater than low heel condition ($p = 0.013$).

3.3. Peak utilized contact area

The ANOVA comparing utilized contact area at the time of peak stress among the 3 shoe conditions was significant ($p = 0.02$; Table 1). Utilized contact area at the time of peak stress was significantly greater during high heel condition when compared with medium heel ($p = 0.000$) and low heel ($p = 0.000$) conditions. Additionally, utilized contact area at the time of peak stress during medium heel condition was significantly greater when compared to low heel condition ($p = 0.001$).

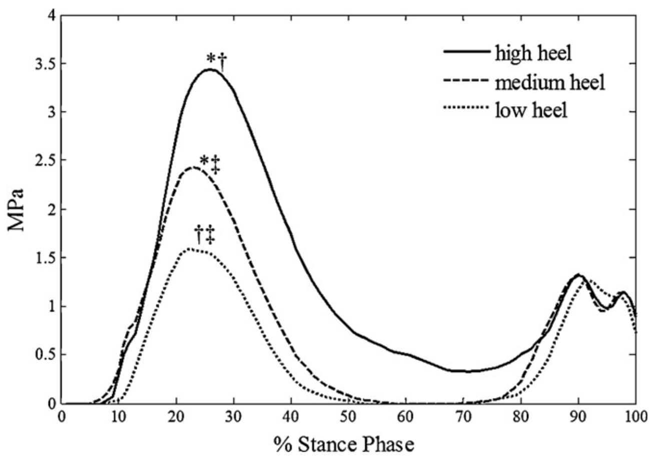

Fig. 3. Patellofemoral joint stress during stance phase for the three shoe conditions. * indicates significant difference from low heel condition ($p < 0.016$); † indicates significant difference from medium heel condition ($p < 0.016$); ‡ indicates significant difference from high heel condition ($p < 0.016$).

3.4. Net knee joint moment

The ANOVA comparing knee extensor moment at the time of peak stress among the 3 shoe conditions was significant ($p = 0.005$; Table 1). During the high heel condition, knee extensor moment at the time of peak stress was significantly greater when compared to medium heel ($p = 0.000$) and low heel ($p = 0.000$) conditions. Additionally, knee extensor moment at the time of peak stress during medium heel condition was significantly greater when compared to low heel condition ($p = 0.004$).

3.5. Knee flexion angle

The ANOVA comparing knee flexion angle at the time of peak stress among the 3 shoe conditions was significant ($p = 0.01$; Table 1). During the high heel condition, knee flexion angle at the time of peak stress was significantly greater when compared to medium heel ($p = 0.01$) and low heel ($p = 0.000$) conditions. Additionally, knee flexion angle at the time of peak stress during medium condition was significantly greater when compared to low heel condition ($p = 0.01$).

4. Discussion

The primary purpose of the current study was to determine if heel height increases patellofemoral joint stress during walking. On average the high heel condition resulted in a significant increase in peak patellofemoral joint stress (89.5%) compared to the low heel condition. When compared to the medium heel condition, a 38.5% significant increase in patellofemoral joint stress was observed. As such, our findings support the premise that wearing high-heeled shoes may be a risk factor with respect to the development of PFP.

The elevated patellofemoral joint stress observed with the high-heeled shoe condition was driven primarily by an increase in the patellofemoral joint reaction force. In turn the elevated patellofemoral joint force was the result of an increase in the knee extensor moment and knee flexion angle. When compared to the

Table 1
Comparison of biomechanical variables of interest among the three heel height conditions. Mean (SD).

Heel height	Peak patellofemoral joint stress (MPa)	Patellofemoral joint reaction force at the time of peak stress (N/kg)	Utilized contact area at the time of peak stress (mm^2)	Knee extensor moment at the time of peak stress (Nm/kg)	Knee flexion angle at the time of peak stress (degree)
Low	1.9 (0.7)†,‡	5.2 (3.0)†,‡	157.0 (19.1)†,‡	0.4 (0.2)†,‡	16.1 (5.1)†,‡
Medium	2.6 (1.2)*,‡	8.4 (4.0)*,‡	180.0 (20.6)*,‡	0.6 (0.3)*,‡	22.1 (5.9)*,‡
High	3.6 (1.5)*,†	12.7 (6.0)*,†	192.0 (17.6)*,†	0.8 (0.3)*,‡	26.4 (6.1)*,‡

* Significant difference from low heel condition ($p < 0.016$).
† Significant difference from medium heel condition ($p < 0.016$).
‡ Significant difference from high heel condition ($p < 0.016$).

low heel condition, the patellofemoral joint reaction force at the time of peak stress was found to increase by 144.2% in the high heel condition (Table 1). When compared to the low heel condition, the patellofemoral joint reaction force at the time of peak stress was 61.5% higher in the medium heel condition (Table 1).

Similar to the patellofemoral joint reaction force, the utilized contact area at the time of peak stress also increased with heel height. The elevated utilized contact area observed with the high-heeled shoe condition was due to an increase in the knee flexion angle. However, the magnitude of contact area increase was not enough to offset the increase in patellofemoral joint reaction force. For example, when compared to the low heel condition, the utilized contact area at the time of peak stress only increased by 22.3% in the high heel condition (Table 1). Similarly, the utilized contact area at the time of peak stress increased by only 14.6% in the medium heel condition compared to the low heel condition (Table 1).

The observed increased knee flexion angle and knee extensor moment during high-heeled gait is consistent with what has been reported previously [5,8,14]. However, Snow et al. [15] and Kerrigan et al. [16] have reported that wearing high-heeled shoes does not result in an increase in the peak knee flexion angle and peak knee extensor moment during the stance phase of gait compared to shoes with no heels. This inconsistent finding may result from the varying walking velocities and shoe heights that were evaluated. For instance, Kerrigan and colleagues [16] reported a slower walking velocity during high-heeled gait compared to the flat shoe condition. In the current study, the velocities of high heel and medium heel conditions were matched to that of the low heel condition. Additionally, we examined higher heel heights (medium heels: 6.35, and high heels: 9.53 cm) compared to Snow et al. (medium heels: 3.81, and high heels: 7.62 cm) [15] and Kerrigan and colleagues (3.81 cm) [16].

Repetitive overloading of the patellofemoral joint is thought to result in PFP and patellofemoral joint osteoarthritis [3]. Our results suggest that wearing high-heeled shoes results in elevated patellofemoral joint stress, which could potentially lead to an increase in patellofemoral symptoms. Although the relationship between pain and the frequency of wearing high heels has not been established, Dye has proposed that a small exposure to patellofemoral joint overloading can lead to tissue damage and pain [17]. In turn, it has been reported that a 1 MPa reduction in patellofemoral joint stress can decrease PFP by 56% [17]. A 1 MPa reduction in patellofemoral stress is equivalent to the difference observed between the high and medium shoe conditions. Thus lowering heel height from 9.53 cm to 6.35 cm may have a significant impact on symptoms in persons with current PFP.

There are 2 limitations of our study that should be noted. First, only healthy subjects were evaluated. As such, caution should be taken when generalizing our results to other populations (e.g., persons with PFP). It has been shown that persons with PFP exhibit less contact area compared to pain-free controls [18], which may result in greater patellofemoral joint stress as compared to our current findings. Second, a simplified planar model was used to estimate patellofemoral joint stress. As such, the 3-dimensional joint geometry, patella alignment, and patella kinematics were not taken into consideration. However, this modeling approach has been shown to differentiate between persons with PFP and control subjects [4] and was capable of detecting differences among shoe conditions in the current study.

5. Conclusion

Increasing heel height increases peak patellofemoral joint stress during walking. The increased patellofemoral joint stress was driven mainly by an increase in patellofemoral joint reaction force. This finding suggests that wearing high-heeled shoes may be associated with the development of PFP. As such, heel height should be taken into consideration while prescribing footwear for individuals with patellofemoral symptoms.

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Conflict of interest statement

The authors have no conflict of interest to disclose for this research.

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