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Effect of heel height on patellofemoral joint stress during stair descent

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This study aimed to investigate the effect of heel height on patellofemoral joint stress (PFJS) in young women during stair descent. A total of 25 healthy females were recruited. They were instructed to descend a six-step staircase while wearing heeled shoes of different heel heights: flat heel (1 cm), low heel (3 cm), medium heel (5 cm), and high heel (7 cm). Then, PFJS was calculated using kinematic and kinetic data obtained from a biomechanical model of the patellofemoral joint. Compared with the flat heel condition, the high, medium, and low heel conditions resulted in significant increases in peak PFJS ($P_{high} = 0.001$, $P_{medium} < 0.001$, $P_{low} = 0.018$), peak patellofemoral joint reaction force (PFJRF) ($P_{high} < 0.001$, $P_{medium} < 0.001$, $P_{low} = 0.039$), peak quadriceps force ($P_{high} < 0.001$, $P_{medium} < 0.001$, P

Keywords Heel height, Patellofemoral joint stress, Patellofemoral pain, Stair descent

Patellofemoral pain (PFP) presents symptoms such as anterior knee pain, retropatellar discomfort, and pain along the medial and lateral facets of the patella¹, and it is recognized as one of the most prevalent clinical conditions affecting young adults with lower limb injuries². Chronic PFP has been linked to the development of irreversible patellofemoral arthritis, potentially impairing an individual's capacity to engage in activities of daily living³. This condition is particularly prevalent among young adults, with a higher incidence rate, potentially two to three times greater, in females than in males⁴.

While the pathogenesis of PFP is multifactorial and continues to be a subject of debate, the prevailing biomechanical hypothesis suggests that it is associated with excessive patellofemoral joint loading, particularly aggravated during activities such as stair descent, stair ascent, squatting, and running^{5,6}. Patellofemoral joint stress (PFJS) is derived from a knee joint model in which the patellofemoral joint reaction force (PFJRF) is normalized to the patellofemoral joint (PFJ) contact area. Consequently, interventions aimed at diminishing the PFJRF, increasing the PFJ contact area, or employing a combination of these strategies may effectively alleviate PFJS⁷. Such strategies may not only prevent the onset but also provide relief from PFP⁵. Furthermore, deepening our understanding of the patellofemoral joint kinetics during daily living may contribute to the prevention of PFP in females.

Stair descent, a fundamental and ubiquitous activity in daily life, necessitates increased muscular effort and a more extensive range of motion at the knee joint relative to level walking⁸. Moreover, descending stairs is often associated with greater gait instability, a higher incidence of falls and more cautious motor behavior when compared with ascending stairs^{9–11}. The PFJRF, which depends on the magnitude of the quadriceps force and the knee flexion angle, is anticipated to increase during stair descent¹², suggesting that the stress on the PFJ would correspondingly be higher. Specifically, calculations have determined that the PFJ experiences approximately three times the pressure during stair descent compared with level walking¹³.

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Fig. 1. Simulated stairs.



Fig. 2. The placement of the reflective markers (right) and diagram of the lab setup during stair descent (left).

Young women who perceive high-heeled shoes as a fashionable accessory should be aware that donning such footwear can considerably alter the kinematics and kinetics of the knee joint during level walking, thereby potentially inducing alterations in PFJS. Literature indicates that walking with elevated heel heights is correlated with increased knee flexion ¹⁴, which in turn can result in increased peak knee moments and increased PFJRF. When donning high-heeled shoes, the necessity for increased knee flexion during the stance phase is underscored because it absorbs the heightened vertical shock loading and compensates for the increased plantar flexion of the ankle^{15,16}. Stair negotiation demands an increased range of motion at the joints and enhanced muscular strength in the lower limbs relative to level walking, thereby rendering it a more challenging activity¹⁷.

To the best of our knowledge, no previous studies have examined the effect of heel height in footwear on patellofemoral joint kinetics during stair descent. This study aimed to investigate the effect of heel height on PFJS in young women during stair descent. We also hypothesized that the peak knee extension moment and the peak PFJRF would escalate with increased heel height during stair descent.

Materials and methods

Participants

This study is a single-blind, randomized, balanced crossover experimental design. A total of 25 healthy females, aged 18–25 years with prior experience wearing high-heeled shoes, were recruited and volunteered to participate in this study. The mean age, standing height, and body mass of the participants were 20.88 ± 1.48 years, 166 ± 5.15 cm, and 53.66 ± 5.53 kg, respectively. With a sample size of 25, $\alpha = 0.05$, and $\eta^2 = 0.297$, the statistical power for comparisons in the PFJS under the four heel conditions was found to be greater than 0.80. The inclusion criteria were as follows: (1) foot size of 38 or 39 European shoe sizes; (2) body mass index within the normal range of 18.5–23.9 kg/m². Exclusion criteria were as follows: (1) history of any lower extremity injury within the past 12 months; (2) cardiovascular, musculoskeletal, or neurological disorders; (3) ankle-related illness or surgical history. All participants gave their written informed consent prior to any data being collected, and the study was approved by the Institutional Review Boards at Shandong Sport University (approval number: 2023011). The research complied with the Declaration of Helsinki.

Instruments

The stair descent test was conducted on a simulated staircase (17 cm riser, 29 cm tread) with six steps (Fig. 1) designated for data collection. Ground reaction forces were collected at a rate of 1,000 Hz using two force platforms (AMTI, Inc. Watertown, MA, USA), which were embedded in the third and fourth steps of the staircase¹⁸. A 12-camera motion analysis system (Vicon, Oxford Metrics Ltd., UK) was used to capture kinematic data at 100 Hz¹⁹. A total of 43 reflective markers (14 mm in diameter) were placed on each participant's anatomical landmarks according to the visual 3D model to quantify lower extremity kinematics (Fig. 2).

Four shoes that varied in heel height (flat: 1 cm, low: 3 cm, medium: 5 cm, and high: 7 cm^{20,21}) were used in the study (Fig. 3). All shoes utilized in the study was manufactured by the same company, Fangui Henan



Fig. 3. Four different heel heights of shoes used in this study. From left to right: flat (1 cm), low (3 cm), medium (5 cm), and high (7 cm).





Jiayu Footwear Co., Ltd., China, ensuring consistency in material quality and production standards across all specimens. Except for the flat shoes as the baseline condition, all experimental shoes were dress shoes with stiletto heels (14 mm \times 13 mm). Participants were randomly assigned to different heel height conditions to ensure an unbiased evaluation of the effects on patellofemoral joint kinetics.

Protocol

All testing was conducted at the Biomechanical Laboratory of the Shandong Sport University. Participants wore uniform black, tight-fitting clothes to facilitate accurate placement of reflective markers, and anthropometric data were collected. Participants were also provided footwear in their respective size and asked to descend the staircase several times for each heel height condition to check for proper shoe comfort and fit. The dominant leg was defined as the preferred leg for kicking a football²². After receiving detailed instructions from the researcher, the participants started to descend the staircase with the non-dominant foot for the first step in a step-over-step manner at their comfortable speed under four heel height conditions.

In total, each participant was asked to perform 12 stair descending trials (three trials per shoe condition). A successful stair descending trial was defined as one in which the participant's dominant foot struck within the boundaries of the force plate. Additionally, a 1-min rest was provided between consecutive trials.

Data process

Reflective markers were labeled and digitized using Vicon Nexus software. Visual 3D software (C motion, Inc., Germantown, MD, US) was utilized to quantify sagittal plane joint motions of the knee. Kinematic and kinetic data were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 6 Hz for the kinematic data and 50 Hz for the kinetic data¹⁷. An inverse dynamics approach and the Bressel model (Fig. 4) were used to compute the knee extensor moment. The ground reaction force, defined as the threshold for determining contact and toe-off, should be at least 20 N in the vertical direction. The stance phase was determined to begin with the contact of the dominant leg on the fourth step and to end with the take-off from the same step.

PFJRF during the standing phase of stair descent was calculated using the following equation²³:

$$PFJRF = 2F_Q * \sin\left(\beta/2\right) \tag{1}$$

In the equation, PFJRF denotes the patellofemoral joint reaction force, F_Q represents the quadriceps force, and β refers to the patellar mechanism angle. F_Q was calculated by dividing the knee extensor moment value by the length of the F_Q moment arm. The effective moment arm length values (Y: cm) for relative knee flexion angles (x) were estimated by Bressel²⁴ using the following linear equation:

$$Y = \begin{cases} 0.036x + 3.0, & 0 \le x < 30\\ -0.043x + 5.4, & 30 \le x < 60\\ -0.027x + 4.3, & 60 \le x < 90\\ 2.0, & 90 \le x \end{cases}$$
(2)

The patellar mechanism angle (β) was estimated utilizing a linear regression equation, as presented by Matthews et al.²³:

$$\beta = 30.46 + 0.53 \text{x} \tag{3}$$

Additionally, the PFJ contact area was determined as a function of the knee angle using the data reported by Connolly et al.²⁵ to formulate a predictive equation, as used previously²⁶:

PFJ contact area
$$(x) = 0.0781x^2 + 0.6763x + 151.75$$
 (4)

Finally, PFJS was determined by dividing the PFJRF by the PFJ contact area, as shown in Equation:

$$PFJS (x) = PFJRF (x) / PFJ \text{ contact area } (x)$$
(5)

Statistical analysis

One-way ANOVA with repeated measures was performed to compare the peak PFJS, peak PFJRF, PFJ contact area at the time of peak PFJS, peak quadriceps force, knee flexion angle at the time of peak PFJS, and peak knee extension moment during the stance phase among the four heel heights. Post hoc comparisons, consisting of paired t-tests with Bonferroni adjustment, were employed to detect the difference of variables between shoes. Partial eta squared (η^2) was used to represent the effect size of one-way repeated ANOVA. The thresholds for partial eta squared were as follows: 0.01–0.06, small; 0.06–0.14, moderate; and greater than 0.14, large²⁷. The thresholds for Cohen's d were as follows: 0.2–0.5, small; 0.5–0.8, moderate; and greater than 0.8, large²⁸. The significance threshold was set at 0.05. All statistical analyses were conducted using SPSS software version 21.0 (IBM, Armonk, NY).

Results

Patellofemoral joint stress

The peak PFJS, which refers to the maximum PFJS experienced during the stance phase, consistently occurs within the latter 50% of the stance phase across all four heel heights (Fig. 5A). During stair descent, significant differences of heel height on the peak PFJS were detected (means and standard deviations: flat, 5.88 ± 1.68 MPa; low, 6.62 ± 1.47 MPa; medium, 7.01 ± 1.66 MPa; high, 7.10 ± 2.06 MPa) (Table 1: P < 0.001, $\eta^2 = 0.297$; Fig. 6A). No significant differences were observed in peak PFJS between the low, medium, and high conditions (P > 0.05). Post hoc analysis revealed that the peak PFJS was significantly lower in the flat heel condition compared with the low heel (P = 0.018, Cohen's d = 0.463), medium heel (P < 0.001, Cohen's d = 0.676), and high heel (P = 0.001, Cohen's d = 0.640) conditions.Peak PFJS (MPa): peak patellofemoral joint stress; Peak PFJRF (N/kg): peak patellofemoral joint stress; Peak QF (N/kg): peak quadriceps force; KFA at peak PFJS (°): knee flexion angles at the time of peak patellofemoral joint stress; Peak KEM (N·m/kg): peak knee extensor moment.

Patellofemoral joint reaction force

The peak PFJRF refers to the maximum PFJRF experienced during the stance phase (Fig. 5B). During stair descent, significant differences of heel height on the peak PFJRF were detected (means and standard deviations: flat, 54.56 ± 17.06 N/kg; low, 62.16 ± 13.65 N/kg; medium, 67.81 ± 15.48 N/kg; high, 71.32 ± 21.96 N/kg) (Table 1: P < 0.001, $\eta^2 = 0.621$; Fig. 6B). No significant differences were observed in the peak PFJRF between the low, medium, and high conditions (P > 0.05). Post hoc analysis revealed that the peak PFJRF was significantly lower in the flat heel condition compared with the low heel (P = 0.039, Cohen's d = 0.486), medium heel (P < 0.001, Cohen's d = 0.811), and high heel (P < 0.001, Cohen's d = 0.840) conditions.

Patellofemoral joint contact area

The PFJ contact area at the time of peak PFJS refers to the area of contact between the patella and the femur at the moment when the peak patellofemoral stress occurs (Fig. 5C). During stair descent, significant differences of heel height on the PFJ contact area at the time of peak PFJS were detected (means and standard deviations: flat, $481.32 \pm 76.83 \text{ mm}^2$; low, $489.69 \pm 55.38 \text{ mm}^2$; medium, $507.83 \pm 61.78 \text{ mm}^2$; high, $524.65 \pm 80.20 \text{ mm}^2$) (Table 1: P < 0.001, $\eta^2 = 0.569$; Fig. 6C). No significant differences were observed in the PFJ contact area at the time of peak PFJS between the low, medium, and high conditions (P > 0.05). Post hoc analysis revealed that the PFJ contact area at the time of peak PFJS was significantly lower in the flat heel condition compared with the medium heel (P = 0.037, Cohen's d = 0.376) and high heel (P < 0.001, Cohen's d = 0.551) conditions.



Fig. 5. PFJS (**A**), PFJRF (**B**), PFJ contact area (**C**), quadriceps force (**D**), knee flexion angles (**E**), and knee extensor moment (**F**) during the stance phase for the four shoe conditions.

	Flat heel	Low heel	Medium heel	High heel	Р	η^2
Peak PFJS	5.88 ± 1.68	6.62 ± 1.47	7.01 ± 1.66	7.10 ± 2.06	< 0.001	0.297
Peak PFJRF	54.56 ± 17.06	62.16 ± 13.65	67.81 ± 15.48	71.32 ± 21.96	< 0.001	0.621
PFJCA at peak PFJS	481.32±76.83	489.69 ± 55.38	507.83 ± 61.78	524.65 ± 80.20	< 0.001	0.569
Peak QF	51.23 ± 13.30	58.02 ± 11.65	62.73 ± 13.03	65.13±17.79	< 0.001	0.607
KFA at peak PFJS	60.31±7.18	61.31 ± 5.34	63.06±5.63	64.50 ± 7.12	< 0.001	0.560
Peak KEM	1.38 ± 0.28	1.55 ± 0.26	1.63 ± 0.29	1.64 ± 0.37	0.001	0.541

Table 1. Comparison of the biomechanical parameters of knees under four heel height conditions $(Mean \pm SD)$.

Quadriceps force

The peak quadriceps force refers to the maximum quadriceps force experienced during the stance phase (Fig. 5D). During stair descent, significant differences of heel height on the peak quadriceps force were detected (means and standard deviations: flat, 51.23 ± 13.30 N/kg; low, 58.02 ± 11.65 N/kg; medium, 62.73 ± 13.03 N/kg; high, 65.13 ± 17.79 N/kg) (Table 1: P < 0.001, $\eta^2 = 0.607$; Fig. 6D). No significant differences were observed in the peak quadriceps force between the low, medium, and high conditions (P > 0.05). Post hoc analysis revealed that the peak quadriceps force was significantly lower in the flat heel condition compared with the low heel (P = 0.026, Cohen's d=0.541), medium heel (P < 0.001, Cohen's d=0.873), and high heel (P < 0.001, Cohen's d=0.868) conditions.

Knee flexion angles

The knee flexion angles at the time of peak PFJS refers to the angle of knee flexion corresponding to the moment when peak patellofemoral stress occurs (Fig. 5E). During stair descent, significant differences of heel height on the knee flexion angles at the time of peak PFJS were detected (means and standard deviations:



Fig. 6. Peak PFJS (**A**), peak PFJRF (**B**), PFJ contact area at the time of peak PFJS (**C**), peak quadriceps force (**D**), knee flexion angles at the time of peak PFJS (**E**), and peak knee extensor moment (**F**) during the stance phase for the four shoe conditions.

flat, $60.31 \pm 7.18^\circ$; low, $61.31 \pm 5.34^\circ$; medium, $63.06 \pm 5.63^\circ$; high, $64.50 \pm 7.12^\circ$) (Table 1: *P*<0.001, $\eta^2 = 0.560$; Fig. 6E). No significant differences were observed in the knee flexion angles at the time of peak PFJS between the low, medium, and high conditions (*P*>0.05). Post hoc analysis revealed that knee flexion angles at the time of peak PFJS was significantly lower in the flat heel condition compared with the medium heel (*P*=0.025, Cohen's d=0.420), and high heel (*P*<0.001, Cohen's d=0.587) conditions.

Knee joint moments

The peak knee extensor moment refers to the maximum forceful moment generated by the knee extensors experienced during the stance phase (Fig. 5F). Interestingly, peak PFJS, peak PFJRF, and peak quadriceps force coincided with the peak knee extensor moment, which occurred at approximately 80% of the stance phase across all heel height conditions. During stair descent, significant differences of heel height on the peak knee extensor moment were detected (means and standard deviations: flat, 1.38 ± 0.28 N· m/kg; low, 1.55 ± 0.26 N· m/kg; medium, 1.63 ± 0.29 N· m/kg; high, 1.64 ± 0.37 N· m/kg) (Table 1: P = 0.001, $\eta^2 = 0.541$; Fig. 6F). No significant differences were observed in the peak knee extensor moment between the low, medium, and high conditions (P > 0.05). Post hoc analysis revealed that the peak knee extensor moment was significantly lower in the flat heel condition compared with the low heel (P = 0.017, Cohen's d = 0.618), medium heel (P < 0.001, Cohen's d = 0.886), and high heel (P = 0.004, Cohen's d = 0.793) conditions.

Discussion

This study aimed to examine the possible increase in PFJS due to changes in heel heights during staircase descent. The results align with the hypothesis that donning high-heeled shoes is linked to an increase in kinetic and kinematic parameters that are associated with PFJS. The conditions of high, medium, and low heel elevations led to notable increments in peak PFJS, peak PFJRF, peak quadriceps force, and peak knee extensor moment when compared with the flat heel condition. In addition, a statistically significant enlargement in the knee flexion angle and PFJ contact area at the time of peak PFJS was found when the high and medium heel conditions were compared with the flat heel condition.

The observed increase in PFJS with high-heeled shoes can be attributed to a reduction in PFJ contact area, an escalation in PFJRF, or a combination of these factors. This study's findings indicate that the heightened PFJS under high-heeled shoe condition is primarily due to an upsurge in the PFJRF, which is associated with increased knee flexion angle and knee extensor moment²⁹. The PFJ contact area at the time of peak PFJS significantly increased with heel height, which can be attributed to the fact that the knee flexion angle also increased with the high-heeled shoe condition. However, the expansion of PFJ contact area at the moment of peak PFJS increase was not substantial enough to counteract the escalation in PFJRF when different heel heights were analyzed. Specifically, compared with the flat heel condition, the PFJ contact area at the time of peak PFJS increased by only 9.0% under the high heel condition and by a mere 5.5% under the medium heel condition. By contrast, the peak PFJRF experienced a significant upsurge of 30.7% under the high heel condition and 24.3% under the medium heel condition when compared to the flat heel condition. This result indicates that while the PFJ contact area increases with higher heel heights, this increase is overshadowed by the more pronounced increase in PFJRF. Consequently, this results in an elevated PFJS, highlighting the potential for increased loading on the joint with the use of high-heeled shoes.

Given that stair descent necessitates a wide range of motion in the lower limbs, an increased knee flexion angle observed in high-heeled gait is often perceived as a compensatory mechanism for the increased plantar flexion of the ankle^{21,30}. This observation aligns with findings from previous studies³¹. Our study shows that the knee flexes more as the heel height of the shoes increases during stair descent, and this rise leads to increased PFJRF³².

The increased knee extensor moment observed during gait while wearing high-heeled shoes is in agreement with prior research, which indicated that high heels can lead to an increase in the knee extensor moment during level walking³³. However, Kerrigan et al.³⁴ proposed that wearing high-heeled shoes does not result in an increase in the knee extensor moment during level walking compared with walking barefoot for young women. The discrepancy may arise from the differences in heel heights examined between the studies. The present study included higher heel values (flat heels: 1 cm, high heels: 7 cm), whereas Kerrigan et al.'s study compared barefoot walking with high heels at 3.8 cm³⁴.

The peak knee moment occurs at approximately 60° of knee flexion during stair climbing³⁵. Specifically, under the flat heel condition, the knee flexion angle reached 60° at the peak knee extensor moment. However, under other heel conditions, the peak knee extensor moment occurred at slightly higher knee flexion angles, ranging from 61° to 65°. This variation is likely due to the significant increase in the knee flexion angle observed as heel height increases, particularly in the latter half of the stance phase. The increased knee flexion angle associated with the wearing of high heels results in a lengthened knee flexion moment arm, consequently contributing to an elevated knee flexion moment²¹.

Our study reveals that the use of high-heeled shoes is associated with a substantial increase in PFJS, which could potentially play a role in the development of symptoms associated with PFP. Literature shows that an increase in PFJS may serve as a mechanical stimulus, potentially leading to the deterioration and irritation of articular cartilage, and may accelerate degenerative changes in the joint³⁶. Cronin proposed that a reduction of one mega pascal (MPa) in PFJS can significantly decrease PFP³⁷. As a result, our findings (PFJS: flat, 5.88 ± 1.68 MPa; low, 6.62 ± 1.47 MPa; medium, 7.01 ± 1.66 MPa; high, 7.10 ± 2.06 MPa) suggest that recommending a reduction in heel height to below 3 cm could serve as a preventative measure to mitigate the risk of PFP for women or to alleviate symptoms in individuals with PFP during stair descent. In the future, researchers could focus on investigating the effect of varying heel heights on the biomechanics of the patellofemoral joint during stair walking and level walking. Such studies are essential in determining the optimal heel height that minimizes the risk of PFP for women or provides relief for those already experiencing PFP symptoms.

When examining the findings of this study, several limitations must be acknowledged. The research exclusively involved healthy individuals within the age range of 18–25 years. Future research should aim to broaden the age spectrum of participants to better understand how age influences the biomechanics of the patellofemoral joint during high-heeled gait. Furthermore, the generalizability of our study's findings is constrained by the modest sample size, which consisted of only 25 healthy participants.

Conclusion

Wearing high-heeled shoes causes an increase in peak PFJS during stair descent, primarily due to an increase in knee moment and knee flexion angle. The result of this study shows that high heels with a height of 3 cm or more may be a risk factor to the development of PFP. As such, young women are advised to choose heels that are below 3 cm in height when wearing high-heeled shoes to descend stairs.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

SX and XY are responsible for participating in the conception, study design, data collection, and writing and submission of the manuscript. WS, and JW are responsible for the study design and revision of the manuscript. DM and GM are responsible for the data management and monitoring of this study.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

This study protocol was approved by the Ethics Committee of Shandong Sport University (approval number:

2023011), and all participants signed the informed consent form before the experiment.

Additional information

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