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THE BIOMECHANICAL CONSEQUENCES OF HEEL ELEVATION ON SPATIOTEMPORAL AND KINEMATIC GAIT PARAMETERS

Shivani Singh[1], Mohd Arshad Bari[1], Fazal Ur Rehman[2], Junaid Ahmad Parrey[3], Arish Ajhar[1]

[1] Department of Physical Education, Aligarh Muslim University, Aligarh, Uttar Pradesh, India
[2] Department of Anatomy, J.N. Medical College, Aligarh Muslim University, Aligarh, Uttar Pradesh, India
[3] Department of Physical Education and Sports, Govt. Degree College Bijbehara, Anantnag Jammu And Kashmir, India

Corresponding author's e-mail: ahmadjunaid232@gmail.com

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ABSTRACT

Background and aim: High-heeled footwear is commonly linked to fashion, elegance, and professionalism; nonetheless, its biomechanical impact on gait, posture, and musculoskeletal health presents considerable challenges. This study examines the impact of varying heel heights on sagittal plane gait parameters, joint kinematics, and implied postural stability.

Material and methods: Ninety healthy female university students, screened for regular footwear habits but naive to the specific experimental shoes, were categorized into three groups based on standardized shoes provided with different heel heights: low (0-3 cm), medium (3-5 cm), and high (>5 cm). Using synchronized high-speed video cameras (sagittal view data analyzed), participants' gait was recorded as they walked trials down a predetermined 7-meter walkway. Silicon Coach Pro 8 software was utilized to assess gait metrics, including stride length, cadence, joint angles (hip, knee, ankle), and velocity, using anatomical landmarks.

Results: Higher heel height was significantly linked to increased maximum ankle plantarflexion (up to 39.0° ± 1.76°), increased maximum knee flexion (up to 26.26° ± 1.85°), and altered ankle dorsiflexion kinematics (peak increased to 8.80° ± 1.68°), as well as shorter strides (by ~13 cm compared to low heels) and slower gait speeds (by ~0.13 m/s compared to low heels). High heels also imply postural changes, inferred from previous literature to include potentially increased lumbar lordosis and anterior pelvic tilt, which are known risk factors.

Conclusion: The results quantitatively demonstrate the biomechanical trade-offs associated with increasing heel height, emphasizing the necessity of ergonomic footwear design and usage guidelines to mitigate negative health impacts. This study reinforces and quantifies the dose-dependent effects of heel height on lower limb mechanics and potential postural consequences.

KEYWORDS

Gait, heel, kinematics, musculoskeletal pain, posture

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INTRODUCTION

High-heeled footwear is widely worn despite its well-documented impact on musculoskeletal health. The fundamental biomechanical challenge arises from the shoe's design, which forces the ankle into a persistent plantar-flexed position. This alters the body's natural alignment by shifting the center of mass forward and upward, compelling the wearer to adopt compensatory strategies to maintain balance[1,2]. These compensations manifest as a cascade of kinetic and kinematic adjustments throughout the lower limbs and trunk, leading to increased forefoot loading, altered muscle activation patterns, and significant stress on the ankle and knee joints[3-5]. Over time, these adaptations can contribute to a range of pathologies, including metatarsalgia, muscle fatigue, joint degeneration, and chronic lower back pain[6,7].

These biomechanical compensations lead to quantifiable changes in gait and posture. Habitual wearers often exhibit a shorter stride length and increased cadence to maintain stability on a reduced base of support[5,8]. Posturally, a common adaptation is an increased anterior pelvic tilt and lumbar lordosis to counteract the forward-shifted center of mass, placing additional strain on the lumbar spine[2,9]. Crucially, the magnitude of these alterations is directly proportional to the height of the heel, with greater heights exacerbating changes in joint mechanics and plantar pressure distribution[3,5,10].

While these general effects are well-established, there is a need for a clearer understanding of the "dose-response" relationship between specific, incremental heel heights and key biomechanical parameters within a controlled population.

Despite extensive research, a comprehensive quantitative understanding of the incremental, dose-dependent biomechanical changes across specific, defined heel height categories within a standardized and controlled environment is still lacking. This study specifically addresses this gap by providing quantitative data on how low, medium, and high heel heights incrementally and significantly impact key sagittal plane gait kinematics and temporal-spatial parameters in a homogenous population.

This study aims to fill this gap by investigating the biomechanical effects of three distinct heel heights low (0-3 cm), medium (3-5 cm), and high (>5 cm) on sagittal plane gait kinematics and temporal-spatial parameters in young adult females. By analyzing variables such as joint angles (hip, knee, ankle), stride length, cadence, and gait velocity, this research seeks to provide a comprehensive quantitative understanding of how increasing heel height incrementally impacts the body's biomechanics during walking. We hypothesize that increasing heel height will result in:

1) Increased maximum ankle plantarflexion and knee flexion angles;
2) Decreased gait velocity and stride length;
3) Increased cadence.

The findings from this study could inform footwear design considerations and provide evidence-based usage guidelines to help mitigate the adverse health effects associated with prolonged or frequent high-heeled footwear use.

MATERIAL AND METHODS

Participants

A power analysis was conducted a priori using G*Power software (Version 3.1.9.7) based on a medium effect size of f = 0.25, alpha = 0.05, and power = 0.80) for a one-way ANOVA, which indicated a minimum of 28 participants per group. Our sample size of 30 participants per group therefore exceeded this recommendation, ensuring adequate statistical power. A total of 90 healthy female university students from Aligarh Muslim University (Aligarh, Uttar Pradesh, India) participated in this study. The sample was recruited via convenience sampling to ensure homogeneity in age and environmental background. All participants were female to control for known gender-based variations in gait patterns[11]. Participants were randomly assigned to one of three heel height groups (n = 30 per group). Randomization was conducted using a computerized random number generator to ensure unbiased group allocation.

Inclusion criteria required participants to be healthy adults without a history of significant musculoskeletal conditions, lower limb injuries (within the past year), neurological disorders, or balance impairments that could affect gait. Participants were also screened to ensure they were not habitual high-heeled footwear users (e.g. wearing heels >5 cm less than once a week), to minimize habituation bias and capture acute responses to the experimental heel heights. Participants also needed to be cooperative and able to follow instructions., "Participants were randomly assigned to one of the three heel height conditions." Exclusion criteria included any history of major surgery affecting gait, diagnosed neurological conditions, significant comorbidities (e.g. diabetes with peripheral neuropathy), intellectual disabilities preventing comprehension, or observable gross biomechanical abnormalities (e.g. severe foot deformities, significant leg length discrepancy). Ethical approval was obtained from the Institutional Review Board, JNMC, AMU Aligarh (Ref: IECJNMC/122), and written informed consent was obtained from all participants prior to data collection. Confidentiality and anonymity were maintained throughout the study.

Research design and footwear

This study employed a between-groups comparative design to analyze the impact of three heel heights on sagittal plane gait kinematics and temporal-spatial parameters. To isolate the effect of heel height, three pairs of standardized court-style shoes were used. The shoes were identical in brand, material (black synthetic leather),

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construction, and heel shape (block heel), differing only in their posterior heel height. All shoes had identical sole stiffness, and the shoes featured a closed, almond toe shape to maintain consistency across conditions. This study focused on comparing the biomechanical effects of varying heel heights in a controlled shoe environment, and therefore did not include a barefoot condition as a baseline. The groups were defined as:

- Group 1 (Low Heel, LH): 0-3 cm heel height.
- Group 2 (Medium Heel, MH): 3-5 cm heel height.
- Group 3 (High Heel, HH): >5 cm heel height.

Experimental set up and instrumentation

All trials were conducted along a 7-meter walkway in a biomechanics laboratory. This length allowed for acceleration and deceleration, ensuring steady-state gait was captured in the central calibrated volume. This study exclusively utilized 2D sagittal plane video analysis to capture kinematic data, providing a focused perspective on the specific motion parameters." The experimental setup was as follows:

- Camera system: Two synchronized FDR-AX700 4K HDR Camcorders (Sony, Japan) were used for data capture;
- Primary camera (sagittal plane): Positioned 8.5 meters from the walkway's midpoint, with its optical axis perpendicular to the plane of progression to capture sagittal plane kinematics;
- Recording parameters: Video was recorded at 60 frames per second (fps) with a shutter speed of 1/2000s to minimize motion blur;
- Calibration: A standard 3D calibration frame of known dimensions was recorded in the center of the capture volume prior to data collection to enable scaling and spatial measurement in the analysis software.

Procedure

Upon arrival, participants provided informed consent and anthropometric data (age, height, weight) were recorded. Body Mass Index (BMI) was calculated (kg/m^2). Participants wore tight-fitting shorts to ensure clear visibility of anatomical landmarks for marker placement.

As shown in *Figure 1*, markers were carefully positioned on the participant's lower limb based on standard gait and biomechanical analysis protocols.

- *Anterior superior iliac spine (ASIS) marker:* Positioned over the ASIS to capture pelvic movement and hip joint kinematics;
- Greater trochanter marker: Placed laterally over the greater trochanter of the femur to monitor hip joint displacement during motion tasks;
- Lateral femoral epicondyle marker: Affixed over the lateral aspect of the knee joint (femoral epicondyle) to measure knee flexion-extension and rotation;
- Lateral malleolus marker: Positioned on the lateral malleolus of the ankle to assess ankle joint dynamics;
- Calcaneus (heel) marker: Attached at the posterior aspect of the calcaneus to track heel motion during stance and gait phases.
- Fifth metatarsal head marker: Used for analyzing toe-off and foot propulsion during gait.

After a brief familiarization period with the assigned footwear and walkway, participants were instructed to walk at their self-selected, comfortable pace. Each participant performed trials until three successful trials were recorded. A trial was deemed successful if at least one complete gait cycle of the right limb was captured clearly within the calibrated volume, without any signs of targeting, stumbling, or hesitation. Data from these three trials were averaged for final analysis.

Data analysis

The recorded videos were imported into Silicon Coach Pro 8 motion analysis software (Silicon Coach Ltd., Dunedin, New Zealand). The video sequences corresponding to the successful trials were digitized. "Relevant anatomical landmarks (marker centers or visually identified points) were manually digitized frame-by-frame for one complete gait cycle per trial." Or "Semi-automated tracking was used, with manual correction as needed." The 2D coordinates of these landmarks in the sagittal plane were obtained after calibration. Custom algorithms within the software were

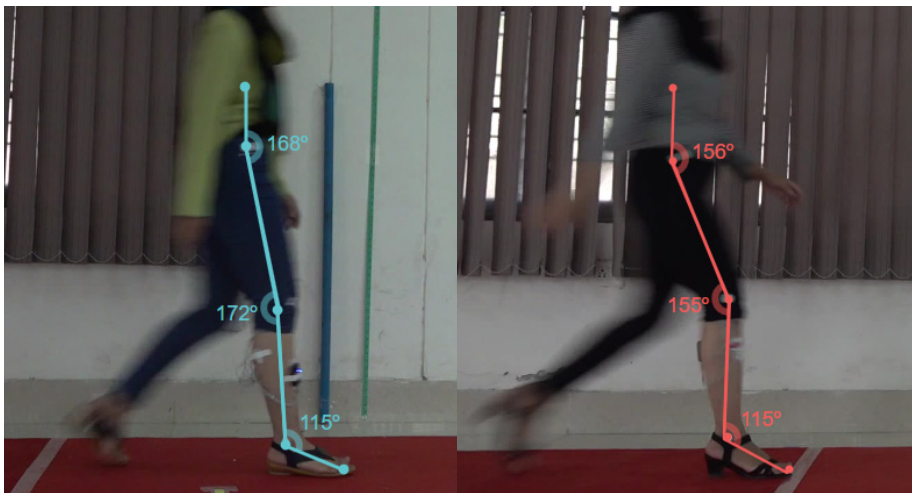


Figure 1. *Marker placement on lower limb.*

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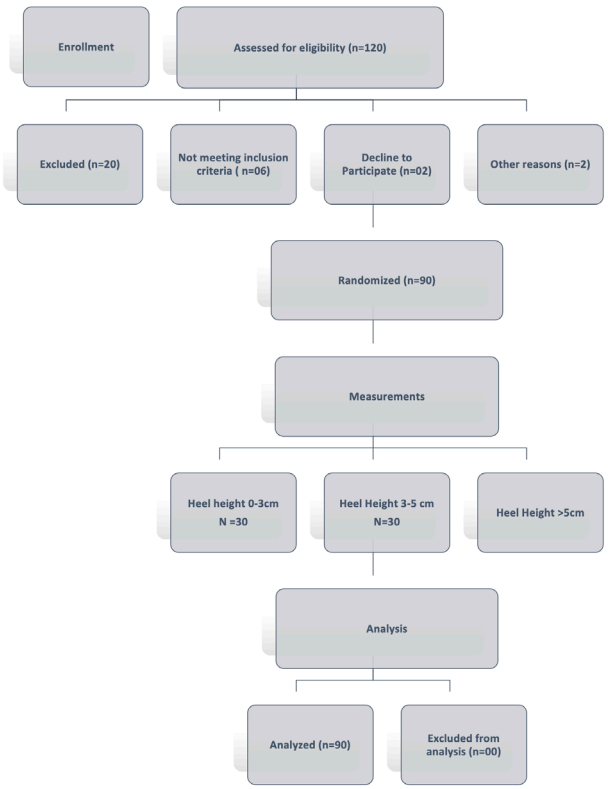


Figure 2. *Flowchart showing the number of participants assessed for eligibility, randomized and analyzed during the study.*

used to calculate the following kinematic variables for the right lower limb throughout the gait cycle:

- Hip flexion/extension angle (angle between trunk/pelvis segment and thigh segment);
- Knee flexion/extension angle (angle between thigh segment and shank segment);
- Ankle dorsiflexion/plantarflexion angle (angle between shank segment and foot segment);

Maximum flexion and extension values for each joint during the gait cycle were identified.

Temporal-spatial parameters were also calculated:

- Gait velocity (average speed over the central stride(s));
- Cadence (steps per minute, calculated from step time);
- Step length (distance between contralateral heel strikes);
- Stride length (distance between ipsilateral heel strikes).

For each participant, the values for each variable were averaged across the three successful trials. Group means and standard deviations were then calculated for each heel height condition.

Statistical analysis

Statistical analysis was performed using SPSS software (Version 27, IBM Corp., Armonk, NY) Descriptive statistics means and standard deviations were calculated for all demographic and kinematic variables for each heel height group. Prior to inferential testing, data were checked for normality using the Shapiro-Wilk test, only after the normality parametric tests were used. A one-way analysis of variance (ANOVA) was conducted for each dependent variable (joint angles, velocity, cadence, step/stride length) to determine if there were statistically significant differences between the means of the three heel height groups. If the ANOVA revealed a significant overall difference ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc test was used to identify which specific group means differed significantly from each other. The alpha level for significance was set at $p < 0.05$. Effect sizes for significant ANOVA results were calculated using eta squared (η^2), with values interpreted following Cohen's guidelines

RESULTS

Table 1 presents the descriptive characteristics of the participants across all three heel height groups (0-3 cm,

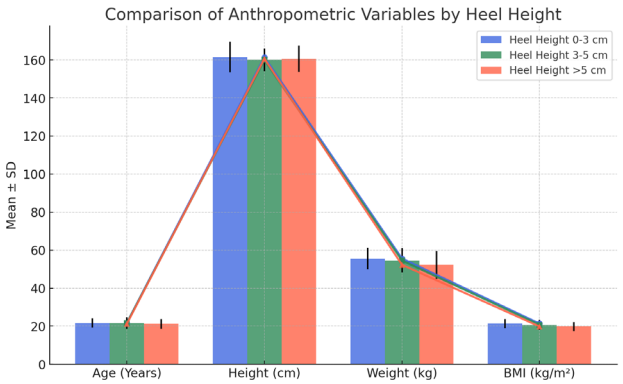


Figure 3. *Graph of demographic characteristics age (years), height (cm), weight (kg), BMI (kg/m²).*

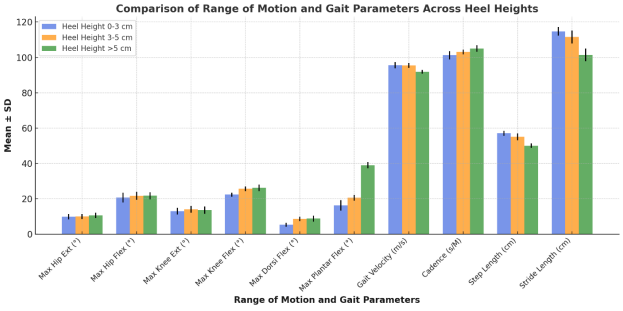


Figure 4. *Graph of descriptive of gait parameters hip extension/flexion, knee extension/flexion, dorsi flexion, plantar flexion, gait velocity, cadence, stride length.*

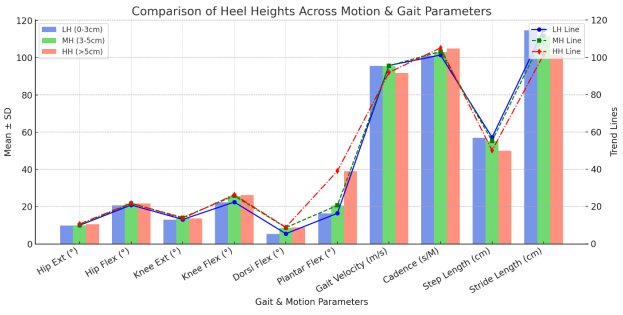


Figure 5. *Graph of comparison of gait parmeters, hip extension/flexion, knee extension/flexion, dorsi flexion, plantar flexion, gait velocity, cadence, stride length.*

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Variable	Group 1 Heel hight 0-3 cm	Group 2 Heel hight 3-5 cm	Group 3 Heel hight >5 cm
	Mean ± SD	Mean ± SD	Mean ± SD
Age (years)	21.70 ± 2.35	21.63 ± 3.11	21.17 ± 2.62
Height (cm)	161.46 ± 7.97	160.00 ± 5.97	160.67 ± 6.92
Weight (ikg)	55.57 ± 5.65	54.57 ± 6.46	52.31 ± 7.31
BMI (kg/m²)	21.33 ± 2.45	20.73 ± 2.60	19.84 ± 2.43

Table 1. *Demographic characteristics of participants (mean ± SD).*

Kinematic Variable	Variables	Heel height 0-3 cm (mean ± SD)	Heel height 3-5 cm (mean ± SD)	Heel height >5 cm (mean ± SD)
Range of motion (°)	**Maximum hip extension angle (°)**	9.83 ± 1.51	9.96 ± 1.37	10.60 ± 1.49
	Maximum hip flexion angle (°)	20.76 ± 2.76	21.63 ± 2.22	21.76 ± 2.01
	Maximum knee extension angle (°)	13.0 ± 2.0	14.03 ± 1.95	13.60 ± 2.15
	Maximum knee flexion angle (°)	22.33 ± 1.18	25.70 ± 1.29	26.26 ± 1.85
	Maximum angle dorsi flexion angle (°)	5.36 ± 1.08	8.63 ± 1.27	8.80 ± 1.68
	Maximum plantar flexion angle (°)	16.30 ± 3.03	20.56 ± 1.65	39.0 ± 1.76
	Gait velocity (m/s)	95.62 ± 1.73	95.49 ± 1.33	91.89 ± 1.09
	Cadence (steps/m)	101.23 ± 2.34	103.10 ± 1.37	105.06 ± 1.91
	Step length (cm)	57.07 ± 1.46	55.12 ± 1.94	50.0 ± 1.26
	Stride length (cm)	114.76 ± 2.47	111.52 ± 3.65	101.44 ± 3.63

Table 2. *Lower limb sagittal plane kinematics and gait parameters for different heel heights (mean ± SD).*

3-5 cm, and >5 cm) were similar in age, height, weight, and BMI, with only minor variations. Mean ages were close, with Group 1 at 21.70 years, Group 2 at 21.63 years, and Group 3 at 21.17 years, indicating similar age distributions. Heights also showed little difference, ranging from 160.00 to 161.46 cm across groups. However, there was a slight trend in weight and BMI, which decreased as heel height increased: Group 1 had the highest mean weight (55.57 kg) and BMI (21.33 kg/m²), while Group 3 had the lowest mean weight (52.31 kg) and BMI (19.84 kg/m²). These subtle differences suggest a possible relationship between body composition and heel height adaptability, which may be relevant in gait studies involving different heel heights.

Table 2 presents the lower limb sagittal plane kinematics and gait parameters for different heel heights (mean ± SD). Maximum hip extension and flexion angles slightly increased with higher heels, with hip extension reaching 10.60° and hip flexion 21.76° in the >5 cm group. Maximum knee extension showed minimal changes across heel heights, but knee flexion significantly increased from 22.33° at the lowest heel height to 26.26° at the highest. Ankle dorsiflexion and plantarflexion angles were also greater with increased heel height, with maximum dorsiflexion rising from 5.36° to 8.80° and plantarflexion drastically increasing from 16.30° to 39.0°. Gait velocity decreased slightly from 0.95 m/s in the 0-3 cm group to 0.91 m/s in the >5 cm group, while cadence increased as heel height rose, reaching 105.06 steps/min in the highest heel group. Additionally, step length and stride length decreased with increased heel height, with the >5 cm group showing the shortest lengths at 50.0 cm and 101.44 cm, respectively.

Table 3 presents the results for one-way analysis of variance (ANOVA) for kinematic variables among different heel heights. Maximum knee flexion, ankle dorsiflexion, and ankle plantarflexion angles showed statistically significant differences between the groups ($p < 0.05$), with large effect sizes for knee flexion ($\eta^2 = 0.26$) and ankle dorsiflexion ($\eta^2 = 0.31$), and a very large effect size for ankle plantarflexion ($\eta^2 = 0.94$). All temporal-spatial parameters showed statistically significant differences ($p < 0.05$). Gait velocity decreased significantly with increasing heel height, with a large effect size ($\eta^2 = 0.73$) cadence increased significantly with heel height ($\eta^2 = 0.22$). Step length and stride length both decreased significantly and substantially as heel height increased, showing very large effect sizes ($\eta^2 = 0.81$ and $\eta^2 = 0.75$, respectively). Post-hoc tests confirmed

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significant differences between all group pairs for step and stride length (LH > MH > HH).

DISCUSSION

This study investigated the biomechanical effects of varying heel heights (low: 0-3 cm, medium: 3-5 cm, high: >5 cm on sagittal plane lower limb kinematics and temporal-spatial gait parameters in healthy female university students. The findings clearly demonstrate that increasing heel height significantly alters normal gait patterns in a dose-dependent manner, imposing considerable changes on joint mechanics, particularly at the ankle and knee, and modifying temporal-spatial parameters associated with gait stability and efficiency.

Ankle kinematics

The most pronounced effect observed was the dramatic and statistically significant increase in maximum ankle plantarflexion angle with increasing heel height ($\eta^2 = 0.94$, $p < 0.05$). This is an expected mechanical consequence, as the elevated heel forces the ankle joint into a more plantarflexed position throughout the gait cycle[6,7,12]. However, these are potential long-term adaptations inferred from acute kinematic changes. Concurrently, a significant increase in maximum ankle dorsiflexion was also observed ($\eta^2 = 0.31$, $p < 0.05$), primarily distinguishing the low heel group from the medium and high heel groups. This might reflect an increased peak dorsiflexion required during the swing phase for adequate toe clearance, rather than an overall increase in functional range[13].

Knee kinematics

Significant alterations were also evident at the knee joint. Maximum knee flexion during the gait cycle increased significantly with heel height ($\eta^2 = 0.26$, $p < 0.05$). Our findings of increased knee flexion and ankle plantarflexion align strongly with the comprehensive conclusions of recent systematic reviews and meta-analyses, such as Nguyen et al.[13] and Zeng et al.[14], which consistently report similar biomechanical alterations associated with high-heeled walking. Specifically, our quantitative dose-response data like ankle plantarflexion up to 39.0° with high heels provides further specific evidence supporting their general observations regarding. This is widely interpreted as a compensatory strategy to absorb impact forces and maintain stability in response to the forward shift in the body's centre of gravity[12-14]. While effective for immediate stability, this altered strategy may suggest a possible long-term risk for increased patellofemoral joint stress and quadriceps demand, as highlighted in previous work[14,15].

Hip kinematics

At the hip joint, although trends towards slightly increased maximum hip extension and flexion were observed with higher heels, these did not reach statistical significance. This suggests that, within this cohort, the primary kinematic compensations occurred more distally at the knee and ankle. This aligns with findings from some previous studies[7,16], but contrasts with others that reported significant alterations in hip kinematics or pelvic tilt[5,17,18]. Factors such as walking speed, participant experience with heels, and the methodology used (2D vs 3D analysis) may account for these differing results[17,19].

Temporal-spatial parameters

The study found a statistically significant decrease in gait velocity ($\eta^2 = 0.7$, $p < 0.05$) and substantial reductions in both step length ($\eta^2 = 0.81$, $p < 0.05$) and stride length ($\eta^2 = 0.75$, $p < 0.05$) as heel height increased. This pattern of adopting shorter, slower steps is a well-documented adaptation to the instability of walking in high heels[8,17,19,20]. This strategy enhances stability by reducing forward momentum and the demands on dynamic balance control, which are compromised by the smaller base of support[21-23]. Conversely, cadence showed a significant increase with higher heel heights ($\eta^2 = 0.22$, $p < 0.05$). Taking more frequent, shorter steps helps maintain a degree of forward progression while minimizing the duration of single-limb support, likely at the cost of reduced overall gait efficiency[18,23,24].

Broader implications and limitations

The biomechanical changes observed in this study, particularly the forced ankle plantarflexion and compensatory knee flexion, are biomechanically linked to postural shifts not directly measured here, such as increased anterior pelvic tilt and lumbar lordosis[23,25,26]. These postural adaptations are widely considered a major contributor to the high prevalence of low back pain among habitual high heel wearers. Our findings underscore the need for footwear designers to consider the biomechanical trade-offs of heel height. Incorporating design features that mitigate excessive ankle plantarflexion or knee flexion, such as optimized heel-to-toe drop or improved stability features, could be crucial. These quantitative results provide clear evidence for public health initiatives aimed at educating wearers about the immediate biomechanical costs of high heels, promoting informed choices regarding heel height and duration of wear to prevent long-term musculoskeletal issues. Clinicians treating conditions like metatarsalgia, Achilles tendinopathy, or knee pain could benefit from understanding these dose-dependent effects when advising patients on footwear choices or designing rehabilitation programs that address compensatory gait patterns.

Crucially, while our findings demonstrate significant acute changes in gait, they should be interpreted with caution regarding long-term pathology. The development of conditions such as Achilles tendinopathy, knee osteoarthritis, or metatarsalgia from chronic wear is a plausible hypothesis supported by these kinematic alterations. However, these potential long-term risks require

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longitudinal validation to establish causality. Our cross-sectional design effectively provides a "snapshot" of the immediate biomechanical cost of wearing heels, but cannot track the cumulative stress that leads to injury. Future longitudinal studies incorporating kinetic and EMG analysis are needed to fully understand the tissue-level loading and neuromuscular adaptations over time. Our results reinforce the clear dose-response relationship between heel height and the magnitude of biomechanical alteration – the higher the heel, the greater the deviation from normative kinematics and temporal-spatial gait patterns. The non-significant findings at the hip in our study emphasize that compensatory strategies can vary, potentially focusing more distally depending on the specific task constraints and individual factors.

Limitations

Several limitations should be considered when interpreting these findings. The study sample consisted of young, healthy female university students from a specific geographic location. These results may not be directly generalizable to older populations, individuals with pre-existing musculoskeletal conditions, males, or populations with vastly different anthropometrics or cultural footwear practices. This was a cross-sectional comparative study using a between-groups design. While it demonstrates differences associated with heel height, it cannot establish causality regarding long-term health effects or track individual adaptation patterns over time. A longitudinal design would be required for such insights. The biomechanical changes observed in this study, particularly the forced ankle plantarflexion and compensatory knee flexion, are biomechanically linked to postural shifts inferred from the existing literature, such as increased anterior pelvic tilt and lumbar lordosis[23,25,26]. Gait analysis was restricted to the sagittal plane using 2D video analysis.. A 3D motion capture system would provide a more complete kinematic description. The study did not include kinetic analysis (ground reaction forces, joint moments, powers) or muscle activity measurement (electromyography - EMG). These data would provide crucial insights into the loading experienced by joints and the neuromuscular control strategies employed. Future studies could expand on this by incorporating longitudinal designs to assess long-term effects, recruiting more diverse populations (males, older adults), and investigating gait on varied surfaces.

CONCLUSION

In conclusion, this study provides quantitative evidence that increasing heel height progressively alters lower limb kinematics and temporal-spatial gait parameters in young women. This study quantitatively demonstrates the dose-dependent biomechanical trade-offs of increasing heel height, showing significant alterations in lower limb kinematics and gait parameters. These findings underscore the importance of ergonomic footwear design and informed usage guidelines to mitigate potential musculoskeletal health risks associated with high-heeled footwear. The results demonstrate a clear dose-dependent relationship, where higher heels lead to significant kinematic compensations most notably increased ankle plantarflexion and knee flexion and a more cautious gait pattern characterized by slower velocity, shorter strides, and higher cadence. This study identifies acute biomechanical alterations that impose considerable stress on the lower limb joints. While these findings are not direct evidence of long-term pathology, they highlight mechanisms that may be relevant to long-term musculoskeletal health and could contribute to an increased risk of acute injuries, such as falls or ankle sprains. These conclusions must be considered in light of the study's limitations. Further research utilizing 3D motion capture, kinetic analysis (force plates), EMG to study muscle activation, and direct measures of postural stability would provide a more holistic understanding. Exploring the impact of heel design innovations (wider heels, cushioned soles) also represents a promising avenue for future investigation into mitigating negative effects." Nevertheless, our results underscore the clear biomechanical trade-offs of high-heeled footwear and highlight the importance of informed choices regarding heel height and duration of wear to mitigate potential health risks.

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