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The influence of heel height on utilized coefficient of friction during walking

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ABSTRACT

Wearing high heel shoes has been associated with an increased potential for slips and falls. The association between wearing high heels and the increased potential for slipping suggests that the friction demand while wearing high heels may be greater when compared to wearing low heel shoes. The purpose of this study was to determine if heel height affects utilized friction (uCOF) during walking. A secondary purpose of this study was to compare kinematics at the ankle, knee, and hip that may explain uCOF differences among shoes with varied heel heights. Fifteen healthy women (mean age 24.5 ± 2.5 yrs) participated. Subjects walked at self-selected velocity under 3 different shoe conditions that varied in heel height (low: 1.27 cm, medium: 6.35 cm, and high: 9.53 cm). Ground reaction forces (GRFs) were recorded using a force platform (1560 Hz). Kinematic data were obtained using an 8 camera motion analysis system (120 Hz). Utilized friction was calculated as the ratio of resultant shear force to vertical force. One-way repeated measures ANOVAs were performed to test for differences in peak uCOF, GRFs at peak uCOF and lower extremity joint angles at peak uCOF. On average, peak uCOF was found to increase with heel height. The increased uCOF observed in high heel shoes was related to an increase in the resultant shear force and decrease in the vertical force. Our results signify the need for proper public education and increased footwear industry awareness of how high heel shoes affect slip risk.

Unperturbed walking requires that the available friction at the shoe–floor interface exceeds the utilized coefficient of friction (uCOF) of the ambulator. Utilized friction is defined as the friction force required to maintain motion [1] and is calculated as a ratio of resultant shear force to the vertical ground reaction force [2–6]. When utilized friction exceeds the friction available at the shoe–floor interface, a slip is likely to occur [2–5,7]. Previous research has shown that numerous factors can affect uCOF including gait velocity, age, sex, shoe sole hardness and shoe type [2,3,5,6,8].

With respect to shoe type, numerous safety organizations have cited the wearing of high heels as being a risk factor for slips and falls [9,10]. The association between wearing high heels and the increased potential for slipping suggests that the friction demand while wearing high heel shoes may be greater than when wearing low heel shoes. To date, only one study [11] has evaluated the influence of heel height on uCOF. Manning and Jones [11] developed a traction test to indirectly measure uCOF. The study utilized one subject who walked backward on a lubricated floor in high heel shoes (6 cm) while pulling against a spring attached to a load cell anchored to a wall. Using this testing protocol, the authors concluded that high heel shoes were not safe for general use. Although the data of Manning and Jones [11] support the premise that walking in high heels may increase slip potential, there are certain limitations of the study that limit the generalizability of the results. First, the study utilized a single test subject that was walking backwards against resistance which is not an adequate representation of normal ambulation. Additionally, the indirect method of calculating uCOF by dividing the horizontal force on the load cell by bodyweight ignores the ground reaction forces developed between the shoe–floor interface.

Beyond the study of Manning and Jones [11], there is no evidence suggesting that wearing high heel shoes increases the friction demand during walking. Therefore, the purpose of this study was to determine if heel height affects utilized friction during walking. A secondary purpose of this study was to compare kinematics at the ankle, knee, and hip that may explain uCOF differences among shoes with varied heel heights. Based on the reports of various safety organizations and the limited data of Manning and Jones [11], we hypothesized that uCOF would increase with increasing heel height.

1. Methods

1.1. Subjects

Fifteen women between the ages of 22 and 31 volunteered for this study. The average age, height and weight of the study participants were 24.5 ± 2.5 yrs, 1.61 ± 0.05 m, and 56.2 ± 10.0 kg,

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respectively. All subjects had prior experience wearing high heel shoes and were current casual wearers.

Subjects were healthy and capable of independent ambulation. Participants who reported any current orthopedic injury, medical condition, or were possibly pregnant, were excluded from participation. Prior to testing, each subject signed a consent form approved by the Institutional Review Board of the University of Southern California.

1.2. Instrumentation

Walking trials were conducted on 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 (vertical, anterior–posterior and medial–lateral) were recorded at 1560 Hz using an AMTI force plate (Model OR6-6-1000 Advanced Mechanical Technology Inc., Watertown, MA) that was embedded in the middle of the walkway. 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 Metric 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. Shoes were of similar hardness in the forefoot (Low & High 35D, Medium 45D) and heel (Low 45D, Medium & High 60D) as assessed with a durometer (Rex Gauge Co., Buffalo Grove, IL). The forefoot and heel outsole patterns were the same across shoes. Shoes were reused between subjects and monitored for wear. Subjects only were allowed to ambulate on the smooth resilient lab floor to ensure shoe sole characteristics would not be altered throughout the study.

1.3. Procedures

All testing was performed at the Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. The temperature and humidity in the laboratory at the time of testing were 70 °F and 34%, respectively. Subjects were 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 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). 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.

Subjects were instructed to walk at a self-selected velocity for each of the 3 heel height conditions. In total, subjects completed 15 walking trials (5 trials per shoe condition). The order of heel height conditions was randomized; however, trials for each condition were completed consecutively. A trial was deemed acceptable based on 2 criteria. First, the subject's dominant foot had to strike within the boundaries of the force plate. Second, the subject's walking velocity had to be within ± 5% of the first walking trial for that respective shoe condition.

1.4. Data analysis

Reflective markers were labeled and digitized using Vicon 612 software (Oxford Metric Ltd., Oxford, UK). Visual 3D software (C-Motion, Germantown, MD) was used to quantify sagittal plane joint motions of the hip, knee, and ankle based on standard anatomical conventions (i.e. joint motion was defined as distal segment movement relative to the proximal segment). Kinematic data were filtered using a 4th order, 6 Hz, low pass Butterworth filter with zero lag compensation. The kinematic variables of interest included sagittal plane hip, knee and ankle joint angles at time of peak uCOF.

Unfiltered ground reaction forces (GRFs) were used to determine uCOF during stance phase. For each trial, uCOF was calculated as the ratio of resultant shear force to vertical force (Eq. (1)) [5,12].

$$\mathrm{uCOF} = \frac{\text{Resultant shear GRF}}{\text{Vertical GRF}} = \frac{\sqrt{(F_{\text{Anterior–Posterior}})^2 + (F_{\text{Medial–Lateral}})^2}}{F_{\text{vertical}}} \quad (1)$$

During weight acceptance, the peak uCOF value resulting from a shear force that would contribute to the foot sliding anteriorly was identified. To avoid spuriously high uCOF values resulting from division by small numbers [1,13,14] only data after the first 5% of the stance phase was considered for analysis. We felt that this criteria was justifiable as slips typically occur near the end of weight acceptance (i.e.50–100 ms following initial contact) [15–17]. Other kinetic variables of interest included the vertical and resultant shear GRFs at time of peak uCOF and the time (% stance) to peak uCOF.

1.5. Statistical analysis

Separate one-way ANOVAs 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

Fig. 1. The three shoe designs used in this study. Low heel (left), medium heel (center) and high heel (right).