typically in the scanner for less than 15 min, including setting-up time. Third, our perfusion maps allow quantitative measurement of net blood flow within pixels in the placental images, and this may allow us to separate regions of normal perfusion within the intervillous space from regions of infarction with low perfusion.

However, we realise that our results are only preliminary, because of the small sample size studied. At present this study has only been done on single slices taken through the placenta of each patient; errors in assessment could occur if the slice chosen were abnormal. The development of multi-slice perfusion imaging will prevent such errors. Further work is currently being done on a remotely perfused placenta to study methods of separating fetoplacental flow from maternal-placental flow.

In conclusion, we believe that EPI has great potential in the non-invasive assessment of abnormal placental function. The production of non-invasive perfusion maps of the placenta by means of EPI enables us to show an association between reduced placental perfusion and IUGR complication in pregnancy. If mapping of placental perfusion with EPI can give important information about the degree of ischaemia in the placenta, the management of pregnancies complicated by IUGR can be improved.

Contributors

Susan Francis was responsible for mapping and histogram analysis, and carried out data analysis; Keith Duncan recruited patients and did the ultrasound scanning; Rachel Moore did the MR scanning; Philip Baker and Ian Johnson supervised clinical aspects of the study; and Penny Gowland supervised the physics of the study. All investigators contributed to the writing of the paper.

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Knee osteoarthritis and high-heeled shoes

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Summary

Background Little is known about the effects of walking in high heels on joints in the legs. Since osteoarthritis of the knee is twice as common in women as in men, we investigated torques (forces applied about the leg joints) of women who wore high–heeled shoes.

Methods We studied 20 healthy women who were comfortable wearing high-heeled shoes. The women walked with their own high-heeled shoes and barefoot. Data were plotted and qualitatively compared; major peak values for high-heeled and barefoot walking were statistically compared. Bonerroni adjustment was made for multiple comparisons.

Findings Measurement showed increased force across the patellofemoral joint and a greater compressive force on the medial compartment of the knee (average 23% greater forces) during walking in high heels than barefoot.

Interpretation The altered forces at the knee caused by walking in high heels may predispose to degenerative changes in the joint.

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Introduction

Although millions of women wear high-heeled shoes, little is known about the effects of these shoes on the forces acting on leg joints. Most studies have focused on the foot and showed greater forces in the forefoot, particularly in the medial forefoot, implying increased predisposition to forefoot deformities such as hallux valgus.[1–6] Does wearing high-heeled shoes compromise the function of the ankle such that compensations to maintain stability during walking occur in the knee or hip joints? This possibility is pertinent, because osteoarthritis is twice as common in women as in men, and usually occurs bilaterally.[7–9]

Compensations were expected to occur mainly in the sagittal (flexion/extension) plane, although differences were also anticipated in the coronal (varus/valgus) plane. During walking, the weight of the body is medial to the knee, which imposes a varus torque at the knee—a compressive force on the medial aspect and a stretching force on the lateral aspect of the knee.[10] Because walking in high-heeled shoes shifts the weight of the body medially with respect to the foot,[2,4,11] we postulated there would be a greater than normal varus torque at the knee. A greater varus torque implies a greater compressive force on the medial aspect of the knee, which could be important because osteoarthritic changes are more common in the medial than in the lateral aspect of the knee.[12] We measured joint torques at the hip, knee, and ankle[13-17] in women walking barefoot and in high heels.

Methods

20 healthy women who felt comfortable wearing shoes with narrow heels at least 5 cm high were recruited. We excluded platform shoes or those with a high-contact area of more than 2 cm width. The study was approved by our Institutional Review Board and written informed consent was obtained from each woman. The women had a mean age of 34·6 (SD 9·3) years, height of 1·67 (0·06) m, and weight of 61·76 (7·6) kg. Each woman was asked to walk at her comfortable walking speed across a 10 m gait-laboratory walkway, both barefoot and in her own high-heeled shoes. The order for high-heel and barefoot walking was randomised, with a 10 min rest between experiments. The height of the heels was 6·0 (1·0) cm. Barefoot walking served as the control rather than walking in low-heeled shoes, because styles of low-heeled shoes vary widely.

Hip, knee, and ankle-joint torques in sagittal, coronal, and transverse planes were measured on both sides over three trials of high-heeled and barefoot walking. We used standard procedures,[13,16,17] and the specific protocol has been described elsewhere.[14,18] Briefly, a video-based motion-analysis system measured the three-dimensional position of markers attached to various bony landmarks on the pelvis and legs during walking. Ground-reaction forces were measured synchronously with the motion-analysis data by two staggered force platforms imbedded in the walkway (Advanced Medical Technology Inc, Newton, MA, USA). Joint torques in each plane were calculated with a full-inverse dynamic model, SAFLo (Servizio di Analisi della Funzionalita' Locomotoria Bioengineering Technology Systems, Milan, Italy). Joint torque calculations were based on the mass and inertial characteristics of each leg and the derived linear and angular velocities, and acceleration, as well as ground-reaction force and estimates or joint-centre positions. Joint-angle motion in all planes was also studied and reported in degrees with zero defined as the angle during quiet standing while barefoot. Joint torques were adjusted for bodyweight and height and reported in N-m/kg-m.

Joint torques and joint motions were plotted on a graph over the walking cycle (0–100% at 2% intervals). Statistical evaluations were done with Systat 7.0 (SPSS Inc, Chicago, IL, USA). To account for variances between trials and sides, differences between high-heeled and barefoot walking were assessed with a general linear model, which does not assume that the data are balanced, with covariates of trial and side.[19] Bonferroni adjustment was made for the multiple (50) comparisons; statistical significance was defined at p<0·001.

Results

In the sagittal plane, peak ankle torque was significantly reduced with high-heeled shoes (0·60 [SD 0·08] high-heels *vs* 0·75 [0·07] barefoot, mean difference −0·15 [SE 0·013] N-m/kg-m, p<0·001). The pattern of knee torque was different (figure 1), such that with high heels the knee-flexor torque normally present during the early stance phase, extended into the mid-stance phase, and the peak knee-extensor torque during late stance was significantly reduced (0·06 [0·09] *vs* 0·15 [0·06], mean difference −0·09 [0·012] N-m/kg-m, p<0·0001). The hip-torque pattern was slightly altered with a brief rise in hip-flexor torque in early stance with high heels 0·49 [0·13] *vs* 0·42 [0·10]; mean difference 0·07 [0·017] N-m/kg-m, p<0·001).

In the coronal plane, the normal eversion torque at the ankle was significantly reduced with high-heels (peak eversion torque 0·03 [0·03] high heels *vs* 0·12 [0·05] barefoot, mean difference −0·09 [0·008] N-m/kg-m, p<0·0001). The varus torque at the knee was increased throughout the stance period (figure 2), with both peaks significantly greater with high heels than barefoot (0·32 [0·07] *vs* 0·26 [0·07] N-m/kg-m, mean difference 0·06 [0·006] and 0·26 [0·06] *vs* 0·21 [0·08], mean difference

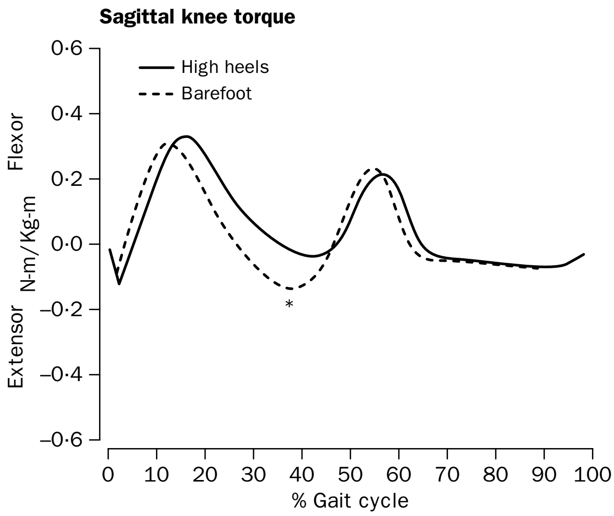

Figure 1: **Sagittal knee joint torque during walking in high-heeled shoes and barefoot**
*Significant difference at p=0·001.

0·05 [0·006] N m/kg m, p<0·0001 for each peak torque). There were no significant changes at the hip or at any of the joints in the transverse plane.

There were significant joint-angle differences between high-heeled and barefoot walking throughout the walking cycle. There was an obvious increase in ankle plantar flexion throughout (mean 20·4° increase, p<0·0001). High-heeled shoes were also associated with greater peak hip flexion than barefoot walking (30·0 [4·3] *vs* 27·0 [5·1]°, mean difference 3·0 [0·65]°, p=0·0002), greater peak knee flexion in stance (22·6 [4·2] *vs* 19·7 [4·6]°, mean difference 2·9 [0·58]°, p=0·0001) and less knee flexion in swing (60·5 [4·3] *vs* 63·5 [4·5]°, mean difference −3·0 [0·42] degrees, p<0·0001).

Discussion

Our findings confirm that wearing high-heeled shoes significantly alters the normal function of the ankle. Because of this compromise, compensations must occur at the knee and hip to maintain stability and progression during walking.[20–22] Our findings suggest that most of these compensations occur at the knee. The prolonged sagittal

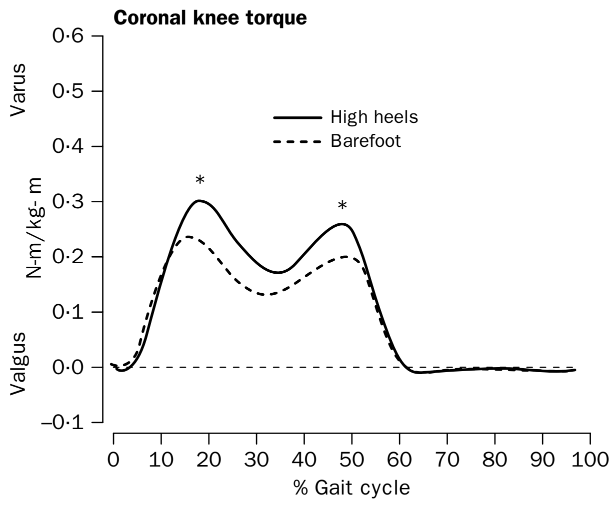

Figure 2: **Coronal knee joint torque during walking in high-heeled shoes and barefoot**
*Significant difference at p=0·001.

knee torque during the stance phase increases the work of the quadricep muscles, prolongs the strain through the patella tendon, and prolongs the pressure across the patellofemoral joint;[23] both the prolonged strain and prolonged pressures may lead to degenerative joint changes within the patellofemoral compartment.

Walking in high-heeled shoes exaggerated the normal varus torque at the knee by an average 23% during the stance period. Greater varus torque imposes greater stretching force through the lateral knee ligaments (and/or greater muscular forces about the lateral aspect of the knee). This increased varus torque is likely to be relevant, since animal experiments show that increasing varus torque at the knee leads to degenerative changes in the medial compartment.[24] Also relevant is that osteoarthritic changes at the knees of human beings are more common in the medial aspect than the lateral aspect of the knee.[12]

We may have underestimated increased medial knee-joint forces because of the limitations of current measurement technology which does not allow for direct measurement of either muscle forces of overall joint compressive forces. Increased varus torque with high-heeled shoes may cause a compensatory increase in lateral muscular forces around the knee to help balance the increased torque. If this is so, overall tibio-femoral compressive forces with high-heeled shoes will be increased, and the magnitude of the medial compressive forces will be greater than our estimated 23% increase. Similarly, prolonged sagittal knee torque implies prolonged force through the quadriceps muscles to balance this torque. Prolonged quadriceps force will cause a prolongation of the overall tibio-femoral compressive forces.

Our findings indicate that much of the compensation for the reduction in torque about the ankle occurs at the knee, rather than the hip. However, a slight increase in hip torque was observed in early stance, consistent with the need for greater hip extensor muscle action during this time. The changes in joint-angle motion we observed accord with other reports: increased ankle plantarflexion throughout walking,[25–28] decreased peak knee flexion,[25,27–29] and increased peak knee flexion in stance.[25,28]

Women wear high-heeled shoes for various reasons.[30–32] The possibility that wearing high-heeled shoes contributes to osteoarthritis at the knee has not been suggested to date. Our findings suggest that further investigations are needed to evaluate a causal relation.

Contributors

D Casey Kerrigan was responsible for the concept, hypothesis, and design of the investigation, and was principally responsible for the interpretation of results and the writing of the manuscript. Mary K Todd collected and analysed the data and contributed to the writing of related portions of the manuscript. Patrick O Riley contributed to the biomechanical interpretation of results and the writing of the manuscript.

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