Footwear Science
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title=content=t795447279

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Online publication date: 13 February 2011

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To cite this Article Hamill, Joseph , Russell, Elizabeth M. , Gruber, Allison H. and Miller, Ross(2011) 'Impact characteristics in shod and barefoot running', Footwear Science, 3: 1, 33 — 40

To link to this Article DOI: 10.1080/19424280.2010.542187
URL: http://dx.doi.org/10.1080/19424280.2010.542187
Impact characteristics in shod and barefoot running

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(Received 27 September 2010; final version received 18 November 2010)

Increased impact characteristics are often cited as a cause of running injuries. One method that has been used to reduce impact characteristics is to increase the thickness of the midsole of running footwear with the intention of attenuating greater shock from the foot-ground collision. A second method that has been suggested is to run barefoot. The purpose of this study was to compare the impact characteristics of running footwear of different midsole thickness to a barefoot condition. Three-dimensional kinematic and kinetic data were collected as participants ran at their preferred running speed and at a fixed speed. Impact characteristics (impact peak, time to impact peak and vertical loading rate) were derived from the vertical ground reaction force component. Ankle and knee joint stiffness during the loading phase of support were derived from the change in moment divided by the change in angle. The impact parameters were statistically analyzed using a two-way, repeated measures ANOVA. There were no significant speed by footwear condition interactions. For impact peak, ankle stiffness and knee stiffness, there was no difference among the shod conditions but there were significant differences between the shod and barefoot conditions. Based on their strike index, participants in this study appeared to alter their footfall pattern from a rearfoot to a midfoot pattern when changing from running shod to barefoot. It may be concluded that the change in the impact characteristics is a result of changing footfall pattern rather than midsole thickness.

Keywords: impact forces; barefoot running; shod running; loading; running injury

1. Introduction

Injuries to runners have been well documented since the beginning of the running ‘boom’ in the 1970s (James et al. 1978). Although a great deal of research during the intervening decades has focused on running and running related injuries, the percentage of runners who get injured has remained essentially the same (Clement et al. 1981, Taunton et al. 2002). Some researchers have implicated running footwear as a possible risk factor for running related injuries. Robbins and Waked (1997a) suggested that modern footwear with a thick midsole necessitates a large impact force in an attempt to transform the interface into a more stable surface. They proposed that this mechanism explains the 123% higher injury frequency found in runners who use more expensive footwear compared with those who use lower cost alternatives (Robbins and Waked 1997b). The researchers concluded that modern running footwear may be potentially over cushioned.

Other researchers have argued that running shoes can be part of the solution to running injuries. Divert et al. (2005a) suggested that the purpose of the shoe is to ‘protect the foot and leg structure by means of a damping and low stiffness material’. Milgrom et al. (1992) reported that basketball shoes were superior to normal military boots in preventing stress fractures of the foot and other overuse injuries of the foot. Rome et al. (2008) concluded that their use in footwear with shock absorbing insoles may reduce the occurrence of stress fractures. Hunter et al. (2007) stated that patella misalignment is potentially modifiable through footwear.

A solution that is often offered to the quandary of the effectiveness of footwear in reducing injury risk is the use of ‘minimal footwear’. Minimal footwear can be defined as a shoe with a thin, flexible midsole and outsole and a light, basic upper with little or no heel counter. In terms of overuse injuries, a more minimal design may mean a thinner midsole. If the theory proposed by Robbins and Waked (1997a) suggesting that the midsole masks the magnitude of impact shock is correct, a thinner midsole may allow runners to sense the severity of impacts and adjust kinematics accordingly. In a study by Clarke et al. (1983) using shoes with different midsole hardnesses, it was shown that subjects adjusted their running kinematics in such...
a way that impact forces were not grossly different. This finding was supported by Snel et al. 1985, Nigg et al. (1987) and Hennig et al. (1996). In addition, if a runner lands on the lateral rearfoot portion of the shoe (as with the rearfoot footfall pattern), a thinner midsole may reduce the lever arm between the ground reaction force and the sub-talar joint which, in theory, may reduce the degree of pronation, and possibly reduce the pronation velocity (Nigg 1986) which has been associated with running injuries (Messier and Pittala 1988).

A currently popular extension of the minimal shoe concept is the move to an even more minimal state, barefoot running. Some claim running barefoot allows the athlete to run ‘naturally’, or as nature intended; which could potentially take advantage of the body’s natural shock attenuation and energy return capabilities. However, several researchers have shown that a runner will alter their kinematics when running barefoot versus running shod (De Wit et al. 2000, Divert et al. 2005a,b). These kinematic alterations may affect the impact characteristics during the initial foot-ground contact phase of running. For example, Oakley and Pratt (1988) reported a 40% reduction in vertical ground reaction force loading rate when running in a 63 durometer insole compared to barefoot.

Recently, footwear manufacturers and running enthusiasts have increased interest in ‘minimal’ shoe constructions and also in barefoot running. It is generally believed that reducing the midsole thickness of running shoes will result in alterations of the impact characteristics and also how runners contact the ground, but these theories have not yet been confirmed experimentally. Therefore, the purpose of this study was to determine the impact characteristics as footwear midsole thickness varied and compare these characteristics to barefoot running. We hypothesized that no changes in the impact characteristics would result as midsole thickness decreased but there would be significant changes in impact characteristics between shod and barefoot running.

2. Methods

2.1. Subjects

Ten participants (five females and five males) were used as subjects in this study. The participants had the following characteristics: for the males – age = 29.6 ± 2.9 years, height = 1.74 ± 0.37 m, body mass = 80.7 ± 5.1 kg; and for the females – age = 27.4 ± 3.7 years, height = 1.64 ± 0.43 m, body mass = 60.6 ± 5.8 kg. All participants were regular runners who ran at least 15 km per week and all normally used a rearfoot footfall pattern (i.e. initial contact was made on the heel). None of the participants had known lower extremity injuries at the time of data collection. Each of the participants signed an informed consent form approved by the University Institutional Review Board.

2.2. Experimental set-up

Kinematic and kinetic data were acquired from the right lower extremity of all subjects. Three-dimensional kinematic data were collected at 240 Hz using an eight-camera Qualisys Oqus capture system (Qualisys, Inc., Gothenberg, Sweden). Ground reaction force data were collected synchronously at 1200 Hz using an AMTI force platform (AMTI, Inc., Watertown, MA, USA) that was flush with the running surface. Running speed was monitored by recording the time between two photoelectric sensors placed 6 m apart.

2.3. Protocol

In order to track the motion of the lower extremities, clusters of retro-reflective markers on rigid plastic shells were placed on the thigh, leg and foot (McClay and Manal 1999). In addition, markers were placed on the right and left anterior superior iliac spines (ASIS), the sacrum at the level of the ASIS markers, the heads of the first and fifth metatarsals and the toe. These 17 markers served as tracking markers for the movement trials. Prior to each individual data collection, a standing calibration trial was collected with the subject in quiet stance. To model the lower extremities and the pelvis, ten calibration markers were placed to identify joint centers and segment mass centers. For the standing calibration trial, calibration markers were positioned to define the individual segment geometries and segment coordinate systems. The calibration markers were positioned on the skin overlying: (1) the right and left iliac crests; (2) the right and left greater trochanters; (3) medial and lateral femoral condyles; and (4) medial and lateral maleoli. Following the standing calibration, the calibration markers were removed with only the tracking markers remaining.

Three pairs of custom built shoes (size 8M for women and size 10M for men) with identical uppers but different midsole thicknesses were used in this study. All shoes had the same mass, foam midsole, midsole durometer, last slope and upper. Shoe A had a heel height of 4 mm and thin outsole only in the forefoot; shoe B had a heel height of 12 and 8 mm in the forefoot; and Shoe C had a heel height of 20 and
16 mm in the forefoot. In addition, there was a condition in which the runners ran barefoot (BF). In all conditions, no instructions were given to the runners on how to contact the ground during the run.

Participants were dressed in tight bicycle-type shorts and a tight fitting short-sleeved shirt. They ran along a 25 m runway in which the force platform was 14 m from the start of the run. Each subject was then given a familiarization period running in the experimental area for 5–10 min before data collection began. Participants ran at their preferred speed (mean 3.57 ± 0.41 m s⁻¹) and at a fixed speed (4.0 m s⁻¹ ± 5%) in each of the four footwear conditions for a total of eight conditions per subject. The order of conditions was randomized to prevent an order effect. Ten satisfactory trials in each condition were collected. A satisfactory trial was one in which the subject made a right foot contact on the force platform within ±5% of the prescribed running speed without modifying their gait.

2.4. Data analysis

Kinematic data for the stance phase of each over-ground running trial were digitized using QTM software (Qualisys, Inc.). Synchronized raw kinematic and kinetic signals were exported from the QTM software in .C3D format and processed using Visual 3D software (C-Motion, Inc., Rockville, MD). Raw kinematic data were low-pass filtered using a fourth order, zero-lag Butterworth digital filter. The cut-off frequencies for the low-pass filtering of kinematic were 12 Hz which was determined using a residual analysis (Winter 2005).

Three-dimensional joint angles for the hip, knee and ankle were calculated using an x (flexion/extension), y (abduction/adduction), z (axial rotation) Cardan rotation sequence (Cole et al. 1993). All angles were referenced to coordinate systems embedded in the distal segment. In addition, the metatarsophalangeal angle was calculated as the flexion angle about an axis from the 1st to the 5th metatarsal. A Newton–Euler inverse dynamics approach was employed to calculate the 3D internal moment at the lower extremity joints. Internal joint moments at the ankle and knee were calculated and reported in the coordinate system of the leg segment.

The ground reaction force (GRF) data were filtered at 75 Hz using a recursive fourth-order low-pass digital filter and were subsequently scaled to each participant’s body weight. From the vertical GRF component, the following parameters were calculated: first peak vertical force (IPeak); time to first peak vertical force (TTP) and average vertical loading rate (VLR). VLR was determined as the slope of the force–time profile from 20–80% of the period between initial foot contact and the impact peak. This section of the vertical force–time profile was chosen because it is the most linear portion of the initial loading portion.

Joint torsional loading stiffness was calculated as the change in joint moment divided by the change in joint angle (Stefanyshyn and Nigg 1998, Hamill et al. 2010). This stiffness, often referred to as quasi-stiffness, represents the sum of many individual stiffness measures (Latash and Zatsiorsky 1993). Sagittal plane ankle (AStiff) and knee joint stiffness (KStiff) were determined from initial foot contact to midstance (i.e. maximum knee flexion). Joint moments were scaled to body mass prior to the calculation of the joint torsional loading stiffness.

Strike index (SI) (Cavanagh and Lafortune 1980) was calculated to confirm the footfall pattern used by the participants in each of the conditions. Strike index is the point of intersection of a perpendicular drawn from the center point of pressure at initial foot contact to the long axis of the foot. The point of intersection is then reported as a percent of the total foot length from the heel. All participants had SI < 33% indicating that they were all rearfoot footfall pattern runners during the shod conditions.

2.5. Statistical analysis

All variables were determined for each of 10 trials per participant for each condition (footwear, barefoot) and averaged within the participant and then across conditions. A repeated measures Analysis of Variance (Speed × Conditions × Participants) was used to determine differences between means. A criterion α level of 0.05 was employed. A Tukey post hoc test was used when appropriate. In addition, effect sizes (ES) were determined for all variables to aid in the interpretation of any trends (Cohen 1989). An ES = 0.2 indicated a small effect, ES = 0.5 a moderate effect and ES = 0.8 a large effect.

3. Results

Each participant altered their footfall pattern to a midfoot pattern when running barefoot from their natural rearfoot pattern. With an SI < 33% in the shod conditions, the indication was that the participants used a heel-toe or rearfoot footfall pattern in the shod conditions. However, in the barefoot condition, all of the participants changed their footfall pattern to a
midfoot contact (i.e. SI > 33% but < 66%). Additionally, to verify this change in footfall pattern, we calculated the average ankle touchdown angle. In the three shod conditions, a dorsiflexed position was observed in the shod conditions (11.14 ± 4.46° and 10.67 ± 4.43° at the preferred and fixed speeds, respectively) and a plantar flexed position in the barefoot condition (−7.13 ± 3.00° and −6.58 ± 2.24° at the preferred and fixed speeds, respectively).

For all of the parameters examined in this study, there were no statistically significant Speed × Condition interactions (P > 0.05) indicating that the parameters showed the same trend across conditions when the participants ran at either their preferred speed or the fixed running speed.

An exemplar profile of the vertical ground reaction force component of a single trial for a male participant is presented in Figure 1. For IPeak, there was a significant difference between running speeds (P < 0.05) with moderate to large ES (ES = 0.65–0.77) for each of the footwear conditions between speeds. The IP was always greater at the fixed running speed, which was faster than the preferred speed for all participants (see Figure 2a). However, for both running speeds, IPeak was significantly different between footwear conditions (P > 0.05). The post hoc test revealed that the locus of the difference was between the barefoot and the footwear conditions with a moderate ES between these conditions (ES > 0.61). The barefoot condition’s IPeak was between 0.19 and 0.31 BW less than the three footwear conditions.

For TTP, the results were similar to the impact peak (see Figure 2b). There was a statistically significant difference among conditions with the post hoc test revealing differences between the barefoot and the three footwear conditions (P < 0.05; ES = 1.35 and 3.40). At each running speed, TTP in the barefoot condition was approximately 50% less (12.31 ms versus 24.35, 26.67 and 25.61 ms and 11.97 ms versus 21.70, 23.17 and 24.31 ms for the preferred and fixed speeds) than the footwear conditions.

For VLR (see Figure 2c), there was a significant difference across conditions (P < 0.05) again with the post hoc test indicating that there was a difference between the footwear conditions and the barefoot condition at each running speed. When running at preferred speed, VLR for the barefoot condition was 30.43 versus 72.23, 65.06 and 59.59 BW s⁻¹ for the 4/0, 12/8 and 20/16 mm shoe conditions respectfully. At the fixed speed, VLR for the barefoot condition was 21.26 BW s⁻¹ versus 69.16, 63.03, 55.02 BW s⁻¹ for the 4/0, 12/8 and 20/16 mm shoe conditions respectfully. While not significant, there was a trend to decrease LR with decreasing midsole thickness.

AStiff values are presented in Figure 3a. There was no significant difference (P > 0.05) and only small effect sizes (ES < 0.18) between running speeds. At each running speed, there were no differences between the shod conditions (P > 0.05; ES < 0.19) but there were differences between the shod and barefoot conditions (P < 0.05) with large effect sizes (ES > 1.0).

There was a significant difference between running speeds (P < 0.05) for KStiff with the fixed running speed having greater values than the preferred speed with small to moderate ES ranging from 0.31 to 0.64 (see Figure 3b). However, there were no differences in KStiff across footwear conditions (P > 0.05; small ES < 0.29).
4. Discussion
The purpose of this study was to examine the impact characteristics when running in footwear with similar construction but varied midsole thickness and compare these characteristics to barefoot running. The hypothesis tested was that there would be no changes in the impact characteristics (e.g., IPeak, TTP, VLR, AStiff, KStiff) as a result of midsole thickness but there would be differences in these impact characteristics between shod and barefoot running. The hypothesis was, for the most part, substantiated. For IPeak, TTP, VLR and AStiff, there were no differences among the shod conditions but the shod conditions were significantly different from the barefoot condition. These differences can be explained by the fact that all participants used a heel–toe footfall pattern in the shod conditions but, in the barefoot condition, all of the participants changed their footfall pattern to a midfoot contact. When running barefoot, all subjects contacted the ground with a slightly plantar flexed foot angle, then continued the ground with the heel shortly after.

The magnitude of the impact characteristics of the shod conditions in the current study were similar to those from other studies. The vertical ground reaction force component, from which IPeak, TTP and VLR are derived, is within the magnitude range of comparable studies that used shod running. IPeak, VLR, AStiff and KStiff all show magnitudes comparable to other studies (Stefanyshyn and Nigg 1998, Milner et al. 2006, Hamill et al. 2010).

The IPeak and VLR of the vertical ground reaction force have been associated with running injuries (Hreljac et al. 2000, Milner et al. 2006, Pohl et al. 2009). Barefoot running has recently been advocated to reduce running injuries by altering kinematics to reduce the effect of impact loading (Lieberman et al. 2010). However, several earlier studies have found increased external loading rates during barefoot running (Dickinson et al. 1985, Komi et al. 1987, Lees 1988, Oakley and Pratt 1988, De Clercq et al. 1994, De Wit et al. 2000). These findings are not consistent with the present study which found reduced impact ground reaction force parameters during barefoot running at both preferred and fixed running speeds. It may be that, while our runners altered their footfall pattern to a midfoot initial contact during barefoot running, in the prior studies the runners maintained an initial rearfoot contact. Oakley and Pratt (1988) reported a 40% reduction in VLR when subjects ran shod with a rearfoot footfall pattern compared to barefoot running with a rearfoot footfall pattern. Additionally,these authors saw no difference in loading parameters when comparing shod and barefoot running with a forefoot footfall pattern. This suggests that a change in footfall pattern is responsible for the differences in loading parameters in shod versus barefoot running. However, our findings support those of Squadrone and Gallozzi (2009) and Divert et al. (2005a) who also observed greater initial ground reaction force peaks during shod running.

Figure 2. Mean GRF parameters for all participants for the preferred (black) and fixed running speeds (white): (a) impact peak force; (b) time to peak impact force; and (c) loading rate.
Landing on the anterior portion of the foot during barefoot running has been observed in other investigations (Squadrone and Gallozzi 2009). By altering their footfall pattern to an initial midfoot contact during barefoot running, the participants in the current study reduced the IPeak and the VLR. However, the IPeak in shod heel-toe running is not synonymous with the IPeak in barefoot running. The impact in barefoot running occurs on the midfoot area of the foot while in the shod conditions it is on the lateral aspect of the heel. The apparent impact peak in a midfoot footfall pattern represents the heel touching down after the initial midfoot contact.

In order to accommodate the alteration of foot posture to a slightly more plantar flexed position at foot contact, the midfoot runner employs a necessarily stiffer sagittal ankle joint at initial impact while a less stiff ankle joint is seen in shod running. Greater ankle stiffness is necessary in midfoot patterns to prevent the heel from impacting the ground. The stiffer ankle joint was observed during barefoot running compared to the shod conditions in the current study. While it may appear beneficial to use a midfoot contact based on the reduced impact peak of the vertical GRF, modifications of other impact-related variables (e.g., ankle stiffness) should be considered as well when assessing the pros and cons of different footfall patterns.

Impact attenuation has been associated with the action of knee flexion during the initial portion of the support phase (Derrick et al. 1998). In the present study, there was a non-significant trend towards an increase in knee joint stiffness (KStiff). Divert et al. (2008) reported greater leg stiffness with barefoot running. Leg stiffness may be viewed as a combination...
of all stiffness components in the lower extremity including knee stiffness. Thus, the non-significant increased trend in KStiff in the barefoot condition may indicate that shock attenuation may take place by other means. However, Squadrone and Gallozzi (2009) reported a reduced stride length while running barefoot. Reducing stride length has been shown to decrease impact characteristics and increase shock attenuation (Derrick et al. 1996). The reduced stride length may help to explain why impact characteristics are less and greater attenuation is found in barefoot running. However, if the runner maintains the same stride length (and footfall pattern) during shod and barefoot running, then the impact characteristics would be expected to be greater in barefoot running.

Runners will generally adopt a forefoot or midfoot footfall pattern when running barefoot on a firm surface possibly to avoid heel contact on the hard surface. Lieberman et al. (2010) suggested barefoot running may reduce the incidence of running related injuries because runners would change their footfall pattern to either mid- or forefoot landings. It has also been suggested that forefoot landings may alter the shock attenuation mechanisms during running (Pratt 1989, Williams and Cavanagh 1987). While results of the present study appear to support these contentions, it is not clear what the long-term effect of altering one’s footfall pattern will be on the risk of running injury.

In a recent paper, Lieberman et al. (2010) suggested a thick heel midsole will result in a rearfoot footfall pattern. The converse of this argument may be that a thinner midsole may lead to a change to mid- or forefoot footfall pattern. In each of the shod conditions in the current study, the participants, who were natural rearfoot footfall pattern runners, all maintained the rearfoot pattern throughout even in the footwear condition with no midsole. It would appear that the participants in the current study altered their footfall pattern as a function of not being shod rather than midsole heel height.

5. Conclusions
The current study indicated that impact characteristics are different between shod and barefoot running. However, we also showed that the participants in this study typically altered their footfall pattern from a rearfoot pattern to a midfoot pattern when progressing from shod to barefoot running. Impact characteristics were not affected by a change in midsole height. However, impact characteristics such as IPeak and VLR were reduced in barefoot running compared to the shod conditions. These findings support the contention that the presence of footwear influences impact characteristics, but do not necessarily indicate that running without shoes or with a particular footfall pattern is beneficial for avoiding injury. Long-term prospective studies would be useful to this end. It may be that the change in footfall pattern affects impact characteristics to a greater degree than midsole thickness.

References


