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Polyurethane Replacement Insoles and Tibial Impact Acceleration Characteristics

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Abstract-The impact accelerations associated with heel strike in gait have been advanced as possible causes of injury. This study examined the effectiveness of a commercial pair of polyurethane replacement insoles with respect to attenuating the accelerations experienced during heel strike. Active male subjects (n=10) age 20-30 years were instrumented with a lightweight accelerometer affixed to the distal medial aspect of the tibia. The subjects walked and ran on a motorized treadmill at 1.34, 2.68, and 3.58 m/s for the following conditions: barefoot (BF), barefoot with insole (BFI), running shoe with original insole (S), and running shoe with replacement insole (SI). Acceleration data were collected for 10 heel strikes at each of the four conditions for three treadmill speeds. Data were smoothed with a Fourier filter utilizing spectral analysis to determine appropriate cut-off frequencies. Repeated measures ANOVA revealed differences between peak impact accelerations for BF & S ($p<0.05$) as well as BF & SI ($p<0.05$) at each running speed. Additionally, differences in rise rate (RR) were observed between BF and all other conditions ($p<0.05$) at each running speed. In shod conditions, the shoe seems to be the primary determiner of impact characteristics and replacement insoles had little effect on tibial accelerations.

Keywords*- tibial impact; insoles; heel strike.*

I. INTRODUCTION

During human gait the foot encounters repeated impacts with the ground. Approximately 80% of runners land with first contact near the heel while others tend to land towards the midfoot [1, 2]). At the instant of heel strike the velocity of the foot rapidly decreases to zero. This change in velocity occurs in three dimensions: axially, anterio-posteriorly, and medio-laterally. The shock associated with this deceleration is propagated rapidly throughout the musculoskeletal system. Some researchers have suggested that various running injuries are perhaps linked to this impact of body tissues.

In early animal studies [3, 4, 5] degenerative changes in bone and cartilage as well as osteoarthritis were associated with repetitive impact loading of the musculoskeletal system. In humans, Sullivan, Warren, and Pavlov [6] observed an increased incidence of stress fractures with increased running mileage. Detmer [7] linked some forms of shin splints to repeated impacts while Voloshin and Wosk [8] reported that low back pain maybe related to the impacts as well. Light, MacLellan, and Klenerman [9] reported that these impacts lead to compressive loads in most joints while others will be subjected to shear stress as in the spinal facet and sacroiliac joints. Shear and stretching of the para-osteal tissue surrounding these joints is a likely cause of low back pain [10]. MacLellan [11] hypothesized that the anterio-posterior components of the heel strike impact may eventually lead to Achilles tendinitis through a shear phenomenon which interferes with the limited blood supply to the Achilles tendon resulting in chronic hypoxic changes. Additionally, it has been postulated that repeated impacts sustained by distance runners may increase the rate of red blood cell destruction and may be partially responsible for deficient iron levels found in many distance runners [12, 13]. Despite these numerous studies, the precise mechanisms of impact related injuries are still unclear.

Researchers have utilized skin and bone mounted accelerometers to measure tibial impact accelerations during heel strike under varying conditions. Clarke, Cooper, Clark, and Hamill [14] reported increased tibial accelerations with increased running speeds. Hamill, Clarke, Frederick, Goodyear, and Howley [15] recorded increased tibial accelerations when running on negative surface gradients and decreased tibial accelerations when running on positive surface gradients. Additionally, several researchers have provided evidence that the attenuation of impact accelerations during running may be influenced by kinematics, soft tissue, and pathological conditions [16, 17, 18].

Lafortune and Hennig [19] measured axial, anterio-posterior, and medio-lateral components of tibial impact acceleration utilizing a triaxial accelerometer mounted directly to the tibia. At running speeds of 4.7 m/s the anterio-posterior component exhibited the greatest peak values (7.6 g) followed by the axial component (5.0 g) and the medio-lateral component (4.5 g). Anterio-posterior and axial components were reduced at running speeds of 3.5 m/s while medio-lateral components remained constant. Lafortune [20] used a similar protocol and reported axial components of 3.0 g and 5.1 g, anterio-posterior components of 5.0 g and 8.2 g, and medio-lateral components of 4.7 g and 5.0 g at running speeds of 3.5 and 4.7 m/s, respectively. Utilizing a skin mounted accelerometer, Valiant [21] reported axial accelerations at the tibia of 2.3 g and 8.2 g while walking and running at 1.53 and 3.83 m/s, respectively.

Running shoes are designed to absorb shock, provide stability and motion control. Cook, Kester, and Brunet [22] measured the degradation in shock absorption characteristics of running shoes as a function of running mileage. The running shoes tested retained less than 60% of their original shock absorbing capacity after 250-500 miles of usage.

It is of interest to determine if running shoes might be able to regain some measure of their original shock absorbing capabilities through the use of a commercial pair of replacement insoles. Nigg, Herzog, and Read [23] compared four viscoelastic replacement insoles with the conventional insoles provided in running shoes. There were no differences in the variables describing vertical impact detected between the viscoelastic replacement insoles and the conventional insoles provided in the running shoes. However, the shoes involved were likely unused and had near original shock absorbing capacity. Light, MacLellan, and Klenerman [9] investigated the effectiveness of a highly viscous shock absorbing heel insert during walking in hard sole shoes. The results demonstrated that the viscous insoles of polyurethane construction were effective in reducing the peak tibial impacts as well as reducing the rise rate during walking in hard sole shoes.

This study examined the effectiveness of a commercial pair of polyurethane replacement insoles with respect to attenuating the impact accelerations experienced during heel strike and to determine the potential of such insoles for restoring the shock absorbing capacity of well used running shoes.

II. METHODS

Ten healthy active male subjects of ages 20-30 years with mean body mass 78.9 ± 11.9 kg consented to participate in this study. Each subject was a heel strike runner and was injury free at the time of data collection.

Each subject walked and ran on a motorized treadmill at speeds of 1.34, 2.68, and 3.58 m/s for the following conditions: barefoot (BF), barefoot with replacement insole (BFI), shod with running shoe with original insole (S), and shod with running shoe with replacement insole (SI). Subjects performed the trials in their own running shoes which were prescreened so that they were neither new nor exceptionally worn out, but did have a considerable amount of wear. The intention was to select shoes which could potentially have their shock absorption capabilities restored. The replacement insoles were a commercially available design of polyurethane construction approximately 14 mm thick in the heel section and contoured to the shape of the heel.

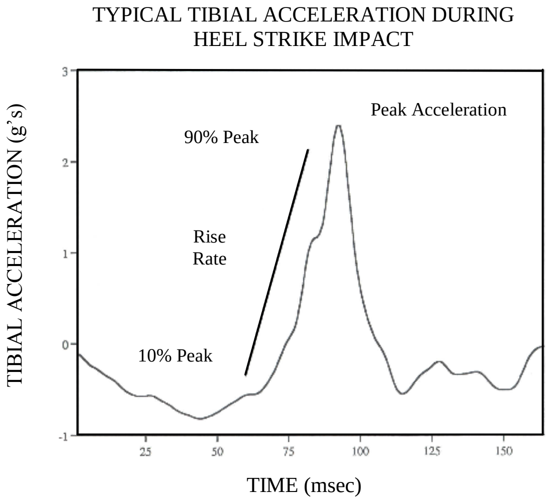

Figure 1. Tibial accelerometer signal near heel strike. The spike portion of the signal corresponds to the heel strike impact and it is the magnitude of this peak value that is reported for various treadmill speeds as well as running surface conditions. Additionally, the rise rate (RR) of the accelerometer signal preceding the peak was determined between 10-90% of the peak signal.

The replacement insoles were affixed to the plantar surface of the foot with double-sided tape for the BFI condition and inserted into the subjects shoes (after removing the conventional insole furnished in the shoe) for the SI condition.

The accelerometer signal was collected for 20 seconds at each treadmill speed (1.34, 2.68, and 3.58 m/s) and foot condition (BF, BFI, S, & SI) for a total of 12 conditions for each subject. The subjects ran for three minutes at each condition to kinematically adjust to the new treadmill speed as well as the foot-treadmill interface before data were collected. The accelerometer signal referenced to 0 g during erect standing was telemetered to a receiver and then converted to digital at 1000 samples per second, using Noraxon hardware and software. Subsequently, data in the heel strike portion of the accelerometer signal were smoothed with a Fourier filter utilizing spectral analysis to determine appropriate cutoff frequencies. For each condition, 10 heel strikes per subject were analyzed. Peak vertical impact accelerations as well as rise rate of the acceleration curve preceding peak were obtained from the acceleration data as illustrated in Fig 1.

Mean of the 10 heel strike peak values and rise rates was used to characterize each subject's response for a given condition. Subsequent analysis proceeded using a repeated measures two factor ANOVA to compare the group responses for speed and foot condition.

III. RESULTS AND DISCUSSION

The intent of this study was to determine the effectiveness of a pair of polyurethane replacement insoles with respect to attenuating impacts encountered during heel strike and to determine the potential of such insoles for restoring the shock absorbing capacity of running shoes lost with extended usage. Four separate conditions at varying treadmill speeds were selected in attempt to answer this question. Barefoot and barefoot with replacement insole were compared in order to focus on the shock attenuating capacity of the insole independent of any running shoe. Manufacture's tests performed by Exeter Research Incorporated scored the replacement insoles (used in this study) 10% above other well known replacement insoles when rated on an insole cushioning index; an index which rates shock absorption and energy return properties of insoles. However, these were material tests and not subject tests as in this study. Several authors [25, 26, 27] have failed to establish a correlation between material and subject testing although Stergiou, Bates, and Davis [28] have demonstrated success in this area utilizing a testing protocol which focused on limiting intra-individual variability. Given the contrasting results of material versus subject testing it was appropriate to test these particular insoles under subject tested conditions.

Researchers have used both skin and bone mounted accelerometers to characterize the impact encountered at heel strike. Various authors have identified the limitations involved with skin mounted accelerometers when compared to bone mounted accelerometers. Hennig and Lafortune [29] estimated that a 6.0 gram skin mounted accelerometer amplified the signal by as much as 50%. It was hypothesized that the relative motion between the bone and soft tissue at impact caused the skin (including mass of accelerometer) to lag behind the bone, stretching and then recoiling, creating excessive acceleration values. Valiant, McMahon, and Frederick [26] reported over estimates of a 4.4 gram skin mounted accelerometer ranging from 17% to 24%, while Gross and Nelson [30] utilizing a 1.0 gram accelerometer identified over estimates of 8%. The results of these studies suggested that skin mounted accelerometers are most accurate when the mass is minimized. Valiant, McMahon, and Frederick [26] suggested that skin mounted accelerometer accuracy can also be improved by strapping the accelerometer to the subject's leg with tension at the subject's level of tolerance. This procedure was followed in this study thereby minimizing the effects of skin mounting the accelerometer. Further, the within-subject measurements involved were performed without any change of accelerometer mounting making within-subject comparison relatively accurate [21].

Despite the limitations of skin mounted accelerometers, their non-invasive nature makes them desirable for data collection as opposed to the more accurate but invasive bone mounted techniques which require surgical procedures for their application. However, acceleration magnitudes from such data collections should be interpreted with caution [20]. Additionally, it should be recognized that the acceleration recorded at the tibia via bone or skin mounted accelerometers is a combination of the acceleration due to gravity, the acceleration due to the angular motion of the shank, and the impact of the limb with the treadmill [19].

Tibial acceleration recordings for a given trial were highly reproducible from heel strike to heel strike (Fig. 2). Peak impact accelerations (g) as well as rise rates (g/s) are presented in Table 1 for each of the 12 conditions. Repeated measures ANOVA revealed significant differences between peak

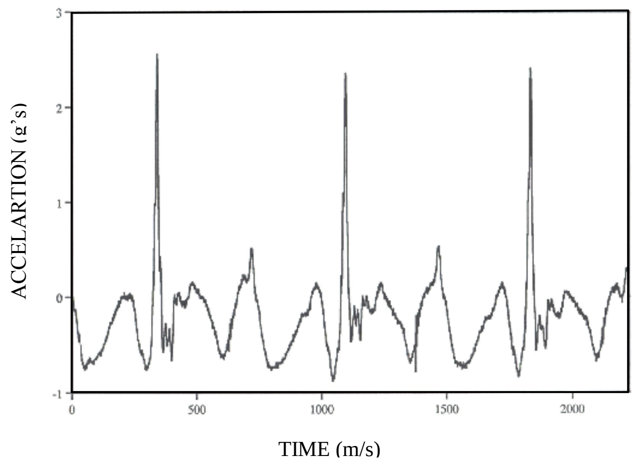

Figure 2. Accelerometer signal for three successive heel strike impacts.

accelerations for BF and S ($p < 0.05$) as well as BF and SI ($p < 0.05$) at each running speed. Additionally, differences in rise rate occurred between BF and all other conditions at each running speed.

Results of this study demonstrated increasing peak accelerations at heel strike with elevated treadmill speeds (when holding foot-treadmill interface conditions constant), which corresponds to the results of Clarke, Cooper, Clark, and Hamill [14] who reported increased tibial accelerations with increased running speeds. Likewise, rise rate increased with elevated running speeds at any given foot-treadmill interface condition.

The BF conditions exhibited the greatest peak accelerations followed sequentially by BFI, S, and SI conditions (Fig. 3.). Heel strike impact accelerations collected during BF conditions ranged from 1.9 to 5.7 g at treadmill speeds of 1.34 and 3.58 m/s respectively. These values fall in a range similar to those previously published [21] of 1.3 and 7.2 g (when corrected for gravity) at treadmill speeds of 1.53 and 3.83 m/s respectively. The BFI conditions ranged from 1.2 to 4.2 g at treadmill speeds of 1.34 and 3.58 m/s respectively. At each treadmill speed the BFI condition exhibited a reduced mean peak impact acceleration as compared to the BF condition; however no statistical significance was detected.

TABLE I. HEEL STRIKE IMPACT ACCELERATIONS AND RISE RATES

	G's			**Rise Rate (g/s)**		
	1.34 m/s	**2.68 m/s**	**3.58 m/s**	**1.34 m/s**	**2.68 m/s**	**3.58 m/s**
BF	1.9 (.7)	3.9 (1.4)	5.7 (2.4)	25.3 (13.7)	58.6 (32.2)	103.5 (84.1)
BFI	1.2 (.4)	2.8 (1.3)	4.2 (2.1)	9.2 (3.5)	27.1 (15.2)	51.6 (46.0)
S	0.8 (.4)	2.0 (.6)	3.2 (1.5)	7.5 (5.0)	15.7 (9.8)	28.8 (23.4)
SI	0.7 (.3)	1.9 (.6)	2.8 (1.1)	6.1 (3.5)	12.2 (8.6)	18.1 (11.3)

Note: Treadmill speeds 1.34, 2.68, and 3.58 m/s. Foot-treadmill interface conditions: BF barefoot, BFI barefoot with replacement insole, S running shoe with original insole, and SI running shoe with replacement insole [mean (STD)].

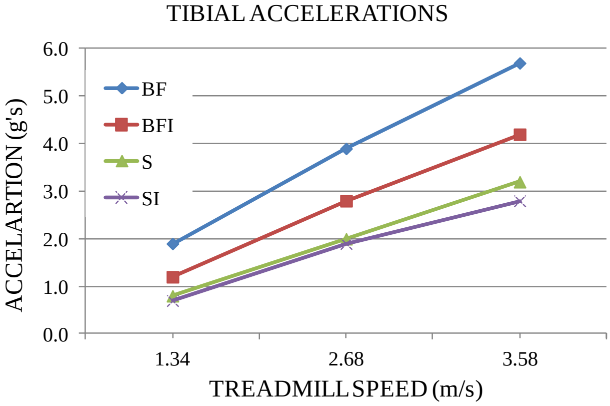

Figure 3. Peak tibial impact accelerations at heel strike for varying treadmill speeds and foot-treadmill interface conditions.

The BF conditions achieved the greatest rise rates followed sequentially by BFI, S, and SI conditions. It appears the replacement insoles alone may reduce the RR which effectively increases the time of impact, assuming peak impact accelerations do not differ. Shorten and Winslow [31] studied the spectral characteristics of the heel strike impact signal and observed that changes in frequency were inversely related to contact time. This implies that larger contact times are related to lower frequency spectral characteristics. Since RR was found to decrease during the BFI conditions and in the absence of significantly differing impact accelerations, impact time probably increased. If this is the case, replacement insoles may be effective in attenuating high frequency components of the heel strike impact. Research into this concept has yielded mixed results. Gillespie and Dickey [32] demonstrated that replacement insoles did reduce high frequency (> 60 Hz) components of the heel strike impact. However, O'Leary et al's [33] spectral analysis of heel strike impacts of four different insoles revealed no change in predominant frequency. The discrepancy between these two studies [32, 33] is likely explained in that O'Leary et al [33] only examined the frequency range of 12-25 Hz, and hence missed the actual frequency range that could be attenuated by the shock absorbing insoles.

Running shoe with original insole (S) versus running shoe with replacement insole (SI) were compared in an attempt to quantify the potential of replacement insoles for restoring the shock absorbing capacity of well used running shoes. The results of this study suggested the replacement insoles did not afford any significant reduction in peak heel strike acceleration over the original insoles provided in the running shoes. These results agree with the findings of Nigg et al. [23] who found no difference between variables describing vertical impact when comparing several different viscoelastic insoles with those provided in the running shoes. The results of the current study and [23] would suggest that it is the shock absorption capacity of the running shoe midsole material as being the primary determiner of impact characteristics with the replacement insole having little effect. Thus, it might be postulated that the poorer the shock absorbing capacity of the shoe, the greater the effect of the replacement insole. This hypothesis would explain the results of Light et al. [9] who demonstrated reductions in the heel strike impact utilizing a highly viscous shock absorbing heel insert during walking in hard-sole shoes. Likewise, this hypothesis would support House et al. [34] who measured reductions in peak pressures at heel strike as a result of introducing three different types of shock absorbing insoles into military boots.

In contrast to the present findings, a review of the Cochrane Data base [35] suggests that shock absorbing insoles "probably reduce the incidence of stress fractures". Leading to the presumption that shock absorbing insoles must be in some manner reducing the negative consequences associated with heel strike impact. Further, a recent study by Creaby et al. [36] concluded that their study "provides new evidence that impact loads are reduced with shoe insoles during walking".

Within the parameters of this study it appears that these polyurethane replacement insoles are probably not effective in improving the shock absorbing capacity of well used running shoes and probably would not extend the functional wear time of running shoes. However, it was noted during the course of the study that all subjects found the replacement insoles to be superior in comfort as compared to the original insoles. Intuitively, one might expect an increased degree of impact attenuation with a subjective feeling of improved cushioning and comfort. However the subjective feelings of cushioning and comfort were more likely a function of improved pressure distribution afforded by the replacement insoles. Because the foot has pressure receptors and not impact receptors, it is possible the subjects sensing this reduction in pressure at heel strike kinematically adjusted their running patterns allowing greater impacts to occur. If this was the case, it would tend to mask the effectiveness of the replacement insoles. Future research efforts of this nature might include kinematic analysis to identify such occurrences.

Heel strike impact components in the anterio-posterior direction were not recorded during this study. MacLellan [11] suggested that the anterio-posterior component of the heel strike was likely the cause of Achilles tendinitis and provided case studies where Sorbothane heel inserts were effective in treating and preventing Achilles tendinitis. It is possible that the replacement insoles used in this study may provide effective attenuation of the anterio-posterior component of the heel strike impact and in this manner extend the functional use of running shoes. Future research efforts of this nature might include impact measures not only in the axial direction but also include the anterio-posterior components as well.

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