EMG and tibial shock upon the first attempt at barefoot running

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\textbf{Abstract}

As a potential means to decrease their risk of injury, many runners are transitioning into barefoot running. Habitually shod runners tend to heel-strike (SHS), landing on their heel first, while barefoot runners tend to mid-foot or toe-strike (BTS), landing flat-footed or on the ball of their foot before bringing down the rest of the foot including the heel. This study compared muscle activity, tibial shock, and knee flexion angle in subjects between shod and barefoot conditions. Eighteen habitually SHS recreational runners ran for 3 separate 7-minute trials, including SHS, barefoot heel-strike (BHS), and BTS conditions. EMG, tibial shock, and knee flexion angle were monitored using bipolar surface electrodes, an accelerometer, and an electrogoniometer, respectively. A one-way MANOVA for repeated measures was conducted and several significant changes were noted between SHS and BTS, including significant increases in average EMG of the medial gastrocnemius ($p = .05$), average and peak tibial shock ($p < .01$), and the minimum knee flexion angle ($p < .01$). Based on our data, the initial change in mechanics may have detrimental effects on the runner. While it has been argued that BTS running may ultimately be less injurious, these data indicate that habitually SHS runners who choose to transition into a BTS technique must undertake the process cautiously.

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1. Introduction

Running is a popular activity for a wide range of people due to its accessibility and the associated health benefits (Novacheck, 1988), including enhanced cardiovascular-pulmonary health, body composition, and general fitness/wellness (Williams, 2009). However, running yields a high injury rate, with up to 79% of runners experiencing an injury annually (Lun, Meeuwisse, Stergiou, & Stefanyshyn, 2004; van Gent et al., 2007). While modern running shoes provide protection for the foot, it has been speculated that modern footwear also has a negative effect on foot function. This is speculated because evolutionarily, humans ran barefoot (Zipfel & Berger 2007). For this reason, many runners are transitioning into barefoot running as a possible means of reducing their risk of injury; specifically overuse, impact-related injury. It has been found that habitually barefoot runners run with a distinctly different strategy than shod runners (Lieberman et al., 2010; Divert, Mornieux, Baur, Mayer, & Belli, 2005). Specifically, barefoot runners predominantly land on their forefoot before bringing their heel down to the ground, a pattern called toe- or forefoot strike (Lieberman et al., 2010). Similarly, a midfoot (flat foot) technique is also commonly used in habitual barefoot runners (Lieberman et al., 2010). Conversely, a large majority (75–80%) of habitually shod runners (runners who run with shoes) land on their heel first (Hasegawa, Yamauchi, & Kraemer, 2007), before bringing their fore-foot down, a pattern called heel- or rearfoot-strike (Nigg, 1988). Amongst other reasons, this pattern manifests itself in shod runners due to the substantial cushioning and height under the heel of modern running shoes. The padding encourages a heel-strike by facilitating a comfortable and more stable landing on the heel.

The differences in foot strike patterns are also commonly associated with differences in impact forces. The impact with the ground sends a wave of shock up the kinetic chain, and thus differences in impact forces can be associated with differences in shock (Derrick, Hamill, & Caldwell, 1998; Hennig, Milani, & Lafortune, 1993). In the first 50 ms of the stance phase of the running cycle, runners who heel-strike produce an impact transient, which can be seen in the vertical ground reaction force trace (Lieberman et al., 2010). These impact transients are related to increased vertical loading rates and tibial shock, which have been associated with the occurrence of bone and soft tissue injuries such as tibial stress fractures and plantar fasciitis (van Gent et al., 2007). Runners who toe-strike, however, do not produce a distinct ground reaction force impact transient (Lieberman et al., 2010).

This lack of an impact transient has created speculation that barefoot running is a less injurious style of running (Lieberman et al., 2010). However, the toe-strike technique is known to cause an increase in pressure under the metatarsal heads (Squadrone & Gallozzi, 2009). Further, Divert et al. (2005) suggest that impact forces are higher in barefoot running until the individual has acclimated to the absence of footwear and acquired proper toe-strike technique. This may pose an additional period of risk to runners who are transitioning into barefoot running. However, the differences in impact and shock upon immediately transitioning from shod, heel-strike into barefoot, toe-strike running have yet to be evaluated.

Differences in foot-strike patterns and footwear have also been shown to have an influence on muscle activity while running (Wakeling & Nigg, 2001), however research on this subject is limited. It has been noted that muscle activity of the tibialis anterior is significantly greater in heel-strike and shod running as compared to toe-strike and barefoot running, specifically, before impact with the ground. This occurs in order to create the necessary dorsiflexion to force a heel-strike as well as to eccentrically control the plantarflexion that is created by the ground reaction force on the ankle (Clarke, Frederick, & Cooper, 1983; von Tscharner, Goepfert, & Nigg, 2003). More research, including work evaluating muscle activity during the stance phase, is necessary to develop a better understanding of the differences between barefoot and shod running, specifically during the immediate transition into barefoot, toe-strike running.

Previous research has produced limited and contradictory results regarding the change in strike patterns associated with the transition from shod to barefoot running. However, the transition from shod to barefoot running requires the runner to have knowledge that they must make a change in their running mechanics to adopt the toe-strike running pattern or the benefits of removing the footwear may be eliminated. It has been suggested that acclimation to barefoot toe-strike running is a slow process, and habitual heel-strikers are unable to immediately adjust their striking patterns to de-
crease the shock (Robbins, Gouw, McClaran, & Waked, 1993; Squadrone & Gallozzi, 2009). Yet, conclusions regarding barefoot running, shod running, and the transition between the two were made either in habitually shod or barefoot populations. It is necessary to examine shod, heel-striking runners’ first attempt at utilizing a barefoot, toe-strike technique in order to understand the risks associated with transitioning from shod to barefoot running.

Therefore, the purpose of this study was to examine muscle activation and tibial shock during the immediate transition from shod to barefoot running. It was hypothesized that muscle activation and tibial shock would increase in the immediate transition from shod to barefoot running.

2. Methods

2.1. Subjects

Eighteen (6 male, 12 female; (Mean ± SD) age = 31.2 ± 7.9 yrs, height = 1.72 ± 0.10 m, weight = 68.6 ± 11.9 kg, km run/week = 20.9 ± 6.0 km) habitually shod, heel-striking, recreational runners participated in this study after providing informed consent approved by the university’s review board. Via a screening form, subjects verified that they were free of any neuromuscular, musculoskeletal, and cardiovascular/pulmonary disorders that may have influenced movement patterns; had not undergone any lower limb surgeries within the year prior to testing; were free of any lower limb musculoskeletal injuries within six months prior to testing; and did not consume any drugs and/or alcohol that may have interfered with motor performance within 24 hours prior to testing. Subjects were also instructed to avoid any strenuous physical activity within 24 hours prior to testing.

2.2. Instrumentation

EMG activity was recorded using bipolar surface electrodes (Delsys Inc., model DE 2.1, 1.0 × 0.1 cm bar electrodes, 1 cm spacing). Heel- and toe-strikes, as well as toe-off, were determined using two foot switches. The raw EMG and foot switch data were collected and amplified (input impedance = 10 MΩ, gain = 1000x, common mode rejection ratio > 92 dB) using a Bagnoli® (Delsys Inc., Boston, MA) EMG system. Tibial shock was recorded using a skin mounted tri-axial accelerometer (Type 8690C5, Kistler Instrument Corp., Amherst, NY), placed directly over the tibial crest. Knee flexion was determined using a custom-built electrogoniometer. All analog data were collected synchronously using a laptop computer equipped with a 16-bit analog-to-digital converter (6036-E, National Instruments Corp., Austin, TX), at a sampling rate of 1000 Hz, with custom designed LabVIEW software (version 8.6, National Instruments Corp., Austin, TX). Subjects conducted all running trials on a TrackMaster® treadmill (model TM500-E AC, Mountain View, CA).

2.3. Experimental protocol

Subjects reported for testing for one session with a testing duration of approximately 60 minutes. Informed consent was obtained and age, height, weight, and average running km/week were recorded. The subject’s dominant leg was then determined using three different functional dominance tests (ball-kick test, step-up test, and balance-recovery test). The leg that was used for at least 2 out of 3 tests (to kick the ball, to step up, and to regain balance) was identified as the dominant leg. Electrode placement was established using finger and handbreadths (Perotto, 1994) over the tibialis anterior (TA) and medial gastrocnemius (MG) muscles. The skin over each muscle belly was shaved (if necessary), abraded, and wiped with isopropyl alcohol before the electrodes were attached. Electrodes were oriented parallel to the direction of the muscle fibers and affixed to the leg with adhesive tabs. Electrode placement accuracy was checked by asking subjects to perform submaximal contractions and checking that only the appropriate muscles activated during each activity. The reference electrode was placed over the spinous process of the C7 vertebrae. Foot switch leads were positioned directly under the calcaneal tuberosity (heel) and the first metatarsal head (ball of the foot). An accelerometer was mounted on the skin over the tibial crest, one handbreadth proximal to the talar dome. The elec-
trogoniometer was attached to the lateral side of the knee with the potentiometer aligned with the knee joint flexion/extension axis.

Subjects then performed a five minute warm-up on a stationary bicycle. Next, subjects were asked to self-select a comfortable speed on the treadmill that would most closely resemble their pace while on an easy distance run (mean test speed 9.5 ± 1.3 km/h). Then, a 7-minute running trial was conducted using their typical running pattern (shod heel-strike (SHS) condition) with EMG, accelerometer, foot switch, and electrogoniometer data collected during the 2nd, 4th, and 6th minutes of the trial. Subjects then took their shoes off and performed another 7-minute running trial, using their typical heel-strike technique (barefoot heel-strike (BHS) condition). After the first barefoot trial, subjects were instructed on the proper toe-strike technique for barefoot running and performed a third 7-minute running trial (barefoot toe-strike (BTS) condition). During all trials, heel- and toe-strikes were verified in real time using the foot switch data, and then exported for analysis. After data collection, subjects were then free to cool down and leave at their own discretion.

Condition order was not randomized for two primary reasons: (1) to allow subjects to warm-up and acclimate to treadmill running using their regular technique; and (2) to prevent prior knowledge of the toe strike technique influencing any of the heel strike conditions. To minimize the impact of fatigue, subjects were given 5 minute rest periods between trials and were asked to report the Rating of Perceived Exertion (RPE) following each minute of data collected. RPE for all trials ranged from 3–5 (out of 10), suggesting a moderate level of exertion.

2.4. Data analysis

Data analyses were conducted using a custom LabVIEW© software program. All data were cropped using the foot switch data, which clipped the data to only include the time when the foot was on the ground (stance) - between touchdown (heel-strike or toe-strike) and toe-off. Touchdowns and toe-offs were determined visually by a trained analyst. The EMG data was band-pass filtered (2nd order, zero-lag Butterworth filter, with cut-off frequencies of 20 and 300 Hz), rectified, and smoothed with a low-pass filter (2nd order, zero-lag Butterworth filter, with a cut-off frequency of 7 Hz). EMG data were then normalized to the maximal EMG activity found in all dynamic trials within each subject for each respective muscle. The dependent variables calculated included: peak shock (peak accelerometer reading during stance), time to peak shock (the time from touchdown to the peak tibial shock), average shock (average tibial shock over the stance phase); TA average and MG average (the average EMG activity during stance for the TA and MG muscles, respectively); TA peak and MG peak (the peak EMG activity during stance for the TA and MG muscles, respectively); knee flexion angle at touchdown (the knee flexion angle when the foot contacted the ground), minimum knee flexion angle (the minimum knee flexion angle during stance (most extended)), maximum knee flexion angle (the peak knee flexion angle during stance (most flexed)); and ground contact time (the time in contact with the ground; the length of the stance phase).

2.5. Statistical analysis

All data were visually inspected and outliers (>3 standard deviations from the mean) were removed. Data were averaged across all strides and measurement times (2nd, 4th, and 6th minutes) for each condition. A single one-way MANOVA with repeated measures was conducted to compare all the dependent variables within the three conditions (SHS, BHS, BTS). Tukey post-hoc tests were utilized to determine which conditions were different once univariate significance was noted. Statistics were performed using SPSS v18.0 statistical software (SPSS Inc., Chicago, IL). The level of significance (α) was set at .05 for all comparisons, a-priori.

3. Results

All the assumptions of the MANOVA (sphericity, homoscedasticity, etc.) were met and a multivariate main effect was found for condition (Roy’s Largest Root, $F(11, 25) = 29.19, p < .01$). Univariate tests
revealed significant differences in ten of the eleven variables analyzed (peak MG activity was the only exception, $p = .11$).

Shock data are presented in Fig. 1. Peak shock was significantly higher in the BHS than SHS condition ($p < .01$) and BHS than BTS condition ($p < .01$). The peak shock was also higher in the BTS than SHS condition.

**Fig. 1.** Peak shock (top; in g), time to peak shock (middle; in ms), and average shock (bottom; in g) in all 3 conditions. *Denotes significant differences ($p < 0.05$).
condition, however this was not statistically significant. The time to peak shock was significantly lower (quicker) in the BHS than SHS ($p < .01$), BTS than SHS ($p = .02$), and BHS than BTS ($p < .01$) conditions. Average shock was significantly greater in the BTS than SHS ($p < .01$) and BTS than BHS ($p = .01$) conditions, with the BTS condition demonstrating the greatest average tibial shock.

EMG data are depicted in Fig. 2. Both average and peak muscle activity of the TA were significantly lower in BHS than SHS ($p < .03$), BTS than SHS ($p < .01$), and BTS than BHS ($p < .01$) conditions. Contrarily, average MG muscle activity was significantly higher in BHS than SHS ($p < .01$) and BTS than SHS ($p = .05$) conditions, while there were no statistically significant differences in peak MG activity.

Knee flexion angle data are depicted in Fig. 3. Knee flexion angle at touchdown was significantly higher in BHS than SHS ($p < .01$), BTS than BHS ($p < .01$), and BTS than SHS ($p = .02$) conditions. Minimum knee flexion angle was significantly higher (most extended) in BHS than SHS ($p < .01$) and
4. Discussion

Peak shock was greater in the barefoot than shod conditions (greatest in BHS). Although not significant, the average difference suggests peak shock was almost 1g greater in BTS than SHS running in the first attempt at BTS running. Further, average shock was found to be significantly greater in the BTS condition than in the SHS condition. The absence of the cushioning from the running shoe is evident from the shock data in the barefoot conditions. Since the foot was in a flatter position at touchdown in the BTS condition, the peak and average shock were lower in BTS than in the BHS condition, where there was no disposition of weight or cushioning for the runner. Greater levels of tibial shock have been related to an increased incidence of overuse injuries, including tibial stress injuries (Hreljac, Marshall, & Hume, 2000). Therefore, our data suggests during the initial transition from shod to barefoot running, a runner may be more vulnerable to lower extremity overuse injuries, such as tibial stress fractures, than when running shod until they properly acclimate to the new toe-strike technique.

The time to peak shock was significantly shorter in the barefoot than shod conditions, although not significantly shorter in the BTS than SHS condition. These results indicate that the peak level of shock was experienced by the runner more quickly and to a greater magnitude in the barefoot conditions than in the shod condition. The shorter time to peak shock in the barefoot conditions may again be partially attributed to the absence of a shoe, which adds a barrier between the runner and the ground that dissipates and delays the transmission of shock up the kinetic chain. Ground reaction force travels up through the leg and is one of the components of tibial shock (Hennig et al., 1993). Since runners experienced faster times to peak shock, it can be speculated that ground reaction forces were experienced up the kinetic chain more quickly during barefoot running as compared to shod. Further, a faster time to peak shock suggests that the vertical loading rate was increased during barefoot running. Since it has been suggested that a factor of lower-extremity stress fractures can be attributed to an increased vertical loading rate, barefoot running may result in an increased risk of skeletal stress injuries over time, if runners do not learn to dissipate that impact more appropriately (Zadpoor & Nikooyan, 2011).

The peak EMG activity was not statistically different in any of the three conditions for the MG muscle, however, the average EMG activity of the MG muscle significantly increased from the shod condition to both of the barefoot conditions. These findings were not surprising since subjects were
habitually shod, heel-striking recreational runners, thus the SHS condition was likely the easiest to perform, thus demonstrating the lowest muscle activity. Further, the toe-strike technique necessitates the use of the plantar flexors to contract eccentrically to absorb the load, thus resulting in greater activation of those muscles. However, the increased average EMG in the barefoot conditions without a significant increase in the peak EMG indicates that the MG muscle may be firing in longer bursts of similar amplitude during the initial transition to barefoot running. The longer bursts of muscle activity during barefoot toe-strike running may indicate that the muscle is firing less efficiently. Since greater, less efficient muscle activity is associated with increased fatigue (Stephens & Taylor, 1972), when transitioning from shod to barefoot running, the runner may become fatigued more quickly. Also, since increased levels of fatigue have been associated with overuse muscle injuries (Fitts, 1994; Mair, Seaber, Glisson, & Garrett, 1996). BTS running during the early transition from shod to barefoot running may lead to an increased incidence of overuse muscle injuries in the lower extremities.

Both the peak and average EMG activity of the TA muscle were highest in the SHS condition and lowest in the BTS condition. The TA muscle creates dorsiflexion, and since the BTS condition requires the foot to be in a plantar flexed position for the forefoot to contact the ground first, the decreased EMG of the TA in that condition highlights the inhibition necessary to allow the foot to plantar flex. The SHS condition likely yielded the greatest peak and average EMG in the TA because the padding in the heel of the shoe necessitates that the foot be in a more plantar flexed position, requiring additional dorsiflexion to heel-strike and more eccentric action to lower the foot down properly after heel strike. It should be noted that the increased EMG in the TA during the SHS running will potentially lead to greater fatigue in that muscle, which may be related to the high injury rates noted in SHS runners. It is possible this is another mechanism by which barefoot running can lead to reduced injury, although more research is required to verify this.

Knee flexion angle was significantly greater at touchdown in the BTS condition than in the SHS condition. Also, the minimum knee flexion (maximum extension) angle was significantly lower in the SHS condition than both the BHS and BTS conditions (BTS highest). This is likely due to the need to absorb the additional impact noted in the barefoot condition from traveling up the kinetic chain. In this light, knee flexion angle may be seen as an indirect measurement of the muscle activity of muscles of the upper half of the leg including the vastus medialis, vastus lateralis and rectus femoris (Westing, Creswell, & Thorstensson, 1991), which would serve to absorb some of that impact. This suggests that there may also be increased muscle fatigue in the musculature of the thigh while running barefoot, which would result in an increased risk of muscle injury in the thigh or the stabilizing structures (ligaments, cartilage, etc.) in the knee which require dynamic support from those muscles. Additional research quantifying muscle activity in the thigh is necessary to verify these findings.

Maximum knee flexion angle was significantly highest in the SHS and lowest in the BTS condition. When coupled with the greater knee extension in the shod running condition, the SHS running technique utilizes a greater range of motion of the knee. This indicates that during the initial transition to BTS running, runners will run with shorter, choppier strides. This conclusion is supported by the significantly shorter ground contact time noted in the barefoot conditions than in the SHS condition. These results are also supported by previous research which found shorter ground contact and flight times in barefoot running than shod running (Divert et al., 2005; Squadrone & Gallozzi, 2009). With short, choppy strides, and less efficient muscle firing, we speculate that during the initial transition, habitual SHS runners are less comfortable running with a BTS technique and thus, may require a transition period to properly acclimate.

Many of the detrimental effects of BTS running shown in this study were probably due to inexperience of the subjects with BTS technique, as these individuals were evaluated during their first attempt at BTS running. Since many runners are choosing to make the transition from shod to barefoot running, it is necessary to learn more about the complete transition from SHS to BTS running over time. This research provides evidence that the early stages of the transition from shod to barefoot running may predispose individuals to a wide range of injuries, and we speculate that until the runner is acclimated to the new technique and the muscles in the leg and foot can appropriately absorb the impact. Our data suggests runners making the transition should not attempt to run long distances with the toe-strike technique early in the transition, especially during their first attempt at BTS running. The transition to BTS running can only be made safely and effectively if the runner is informed...
about the need to adjust their strike pattern (as these data suggest that BHS running is the worst for a runner) and understands that acclimation to this technique is a slow, but necessary process.

One limitation of this study which should be taken into consideration is the testing location and mode; specifically indoors on a treadmill. While all subjects were familiar with running on a treadmill, many of the subjects in this study typically ran outdoors over pavement, in parks, or on trails. Therefore, this may not have represented their typical running style. To reduce the effect of central fatigue runners were asked to run at an “easy, comfortable pace” and took 5 minute breaks in between each 7-minute running trial. Furthermore, since these runners run an average of at least 20 km per week, they likely have a “normal” pace they like to run at, which was reduced or altered to meet the needs of the study. Similarly, they are likely to “get in a groove” when running, which was interrupted with the rest breaks. All of these factors may have resulted in a change in their typical running patterns and mechanics. Additionally, we only used acceleration data from 1 axis (vertical), which may have been affected by limb rotations in the other axes, so the tibial shock data may have been affected. However, the protocol we used was similar to previously published works and should therefore be comparable. Another limitation is the lack of collection of EMG from the thigh musculature, which limited the conclusions which could be drawn. Further, foot type and structure may also have a significant effect on our data, which was not accounted for. Therefore, future work should aim to evaluate the entire lower extremity, from foot type to thigh and hip muscle activity to kinematic and kinetic patterns, such that a better identification the risks and benefits of both running styles and the transition between them could be had.

Future research should also include a longitudinal study in which runners are tested throughout the transition into barefoot running, including re-evaluations not only throughout the transition, but also after their transition is “complete”, to determine how well runners make the transition over an extended period of time. Only then it will be possible to make conclusions about which style of running is potentially less injurious. Furthermore, this type of research may also lead to the development of a transition “schedule” which runners can follow. Also, future research should compare BTS running to running in “minimalist” footwear to evaluate if any differences exist between the two.

5. Conclusion

This study evaluated the effects of the initial transition from shod to barefoot running on tibial shock and muscle activation. It was found that peak shock and average shock were higher in the barefoot conditions, suggesting that stress injuries are more likely to occur while running barefoot during the early stages of the transition. It was also found that the average MG muscle activity was greater in the barefoot conditions than in the SHS condition, while the peak EMG was similar, which suggests that the plantar flexor muscles are firing in longer, less efficient bursts, increasing the likelihood of fatigue. Barefoot running also resulted in a more flexed knee at touchdown, which indicates that muscle activity is likely to be greater in the thigh during barefoot running. Therefore, during the transition to barefoot running, runners may be at a greater risk of developing overuse muscle injuries or risk fatiguing musculature which serves to dynamically stabilize the joints of the lower extremities. Overall, our data suggest there may be a greater risk of injury during the initial transition from shod to barefoot running. This emphasizes the point that the transition must be performed slowly, cautiously, and with knowledge about the proper toe-strike technique in order to avoid potential injury during the acclimation phase.

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