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Reducing Impact Loading During Running With the Use of Real-Time Visual Feedback

Running is a popular form of exercise. In the United States alone, an estimated 12 million people run frequently (100 or more days per year).[1] Unfortunately, overuse injuries, such as stress fractures, are common among runners, with rates ranging from 5% to 16%.[24] Based on these rates, approximately 600 000 to 1 920 000 runners per year will sustain a stress fracture.

Repetitive loading is a key part of the pathophysiology of stress fractures.[3,4,19,36] For stress fractures of the feet and legs, this loading usually comes from activities such as running, marching, and jumping.[8,19] Although the specific characteristics of repetitive loading that lead to stress fractures are unclear, impact loading (ie, loading that occurs as the foot contacts the ground) may play a role. In studies with animals, stress fractures have been produced as a result of impact loads.[5,22] In studies with humans, researchers have examined interventions that use materials designed to cushion impacts to reduce stress fractures.[28,29,40] Thus, if interventions that use materials or footwear to cushion impact loads result in fewer stress fractures, it is likely that impact forces play a role in causing stress fractures.

Evidence from recent studies suggests that tibial stress fractures are related to tibial acceleration and vertical-force loading rates during the early part of stance phase in running.[10,30] In a prospective study of runners, Davis et al[10] collected biomechanical measures from a large group of runners. Some of the subjects developed tibial stress fractures or had tibial stress reactions. The subjects who sustained stress fractures or tibial stress reactions had higher peak positive acceleration of the tibia and vertical-force loading rates prior to their injuries than those in a control group matched for age and running

• **STUDY DESIGN:** Single-subject with repeated measures.

• **OBJECTIVES:** To determine if runners can use real-time visual feedback from an accelerometer to achieve immediate reductions in tibial acceleration and vertical-force loading rates.

• **BACKGROUND:** Stress fractures are a common injury among runners. Previous studies suggest that runners with higher than normal tibial acceleration and vertical-force loading rates are at increased risk for tibial stress fractures. If these runners can be trained to reduce the loading on their lower extremities, it may reduce their risk of stress fractures.

• **METHODS:** Five subjects participated in this study. All subjects ran on a treadmill, instrumented with force transducers, during a single 30-minute session that was divided into warm-up, feedback, no-feedback, and cool-down periods. During running, the subjects also wore an accelerometer taped to their distal right tibia. Peak positive acceleration of the tibia, vertical force impact peak, and average and instantaneous vertical-force loading rates were assessed at the end of the warm-up, feedback, and no-feedback periods.

• **RESULTS:** Single-subject analysis revealed that 4 of the 5 subjects had significant reductions in their peak positive acceleration at the end of the no-feedback period compared to the warm-up. In addition, all of the subjects had significant decreases in impact peak and vertical ground reaction force loading rates at the end of the no-feedback period.

• **CONCLUSION:** In a single session of training with real-time visual feedback, it appears that most runners can reduce the types of lower extremity loading associated with stress fractures. This may lead to training programs that reduce the risk of stress fractures for runners.

• **LEVEL OF EVIDENCE:** Prevention, level 5.
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• **KEY WORDS:** *accelerometer, gait retraining, ground reaction forces, stress fracture, tibia*

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distance. In a retrospective study, Milner et al[30] measured kinematic, kinetic, and structural variables on 20 runners who had previously sustained tibial stress fractures. They also measured the same variables on 20 subjects matched for age and running distance who had never sustained a stress fracture. The results showed that runners with a history of tibial stress fractures had larger peak positive acceleration of the tibia and vertical-force loading rates. There was also a trend for larger-impact force peaks in those with a history of tibial stress fractures. Although retrospective studies, such as the one by Milner et al,[30] cannot be used to determine cause and effect, it is reasonable to expect that even higher peak positive acceleration of the tibia and vertical-force loading rates were present before the subjects sustained their stress fractures. This is because after the stress fracture, it is likely that subjects would try to reduce the loading on the leg that was injured to prevent reinjury. If a runner's mechanics can be modified to reduce tibial acceleration and vertical loading rates, it may be possible to reduce that individual's risk of a stress fracture.

It is unknown whether running mechanics can be modified to reduce tibial acceleration and vertical-force loading rates. However, studies have shown that individuals can be trained to modify other aspects of running, walking, and jumping. A study was conducted in which novice runners were instructed on effective running techniques (ie, techniques expected to improve running economy and reduce perceived effort).[26] There were several significant gait changes made by the experimental group. However, the combination of gait changes did not result in significant differences in running economy or perceived effort between the control group and the experimental group. In case studies, subjects whose instrumented gait analysis revealed abnormal hip and knee angles were trained to run such that these angles were within the ranges of normal runners.[9] In a number of different studies, patients with cerebral palsy, incomplete spinal cord injuries, or total hip replacements, as well as transtibial amputations, have been trained to walk more symmetrically.[13,37,41,43] Various methods have been investigated with regard to training subjects to land from a jump more softly. All of these jump-training methods have resulted in decreases in peak vertical ground reaction forces.[7,17,25,31,34,35,39]

One thing that all of these training studies have in common is that some type of feedback was given to the subjects. This feedback and the way it was presented helped them modify their running, walking, or jumping. The feedback methods included verbal instructions and real-time visual[9,13,26,43] or auditory information.[7,25,37,41] Other studies used verbal instructions and videotape reviews[34,35] or an extensive training program.[17] Interestingly, most of the jump-training studies reviewed only had a single training session for the subjects. However, in most cases, the subjects who received the training with feedback were able to reduce their peak vertical ground reaction force during landing, compared to control subjects who did not get any feedback. The success of the single session of jump training provided motivation for this study to see if individuals could be trained to land softer (ie, with reduced tibial acceleration, vertical ground reaction force impact peak, and vertical-force loading rate) when they run.

The purpose of this study was to determine whether individuals could reduce their tibial acceleration and ground reaction force loading during a single session of gait retraining using real-time tibial acceleration as feedback. We expected that peak tibial acceleration, as well as impact peak and vertical-force loading rates, would be reduced immediately after a 10-minute feedback period. In addition, we expected these reductions to persist after 10 minutes of running without feedback.

METHODS

Subjects

Five physically fit female university students participated. At the time of their enrollment in this study, all the subjects had been running a minimum of 32 km per week for at least 3 months. The subjects' average (SD) age, mass, and height were 26 (2) years, 59.3 (5.4) kg, and 1.64 (0.06) m, respectively. All of the subjects had experienced running on a treadmill. In addition, they were free of any injuries or conditions that might have influenced their running mechanics at the time of the study. This study was approved by the Institutional Review Board at the University of Massachusetts. Each subject read and signed a statement of informed consent before participating.

Procedures

A uniaxial accelerometer (PCB Piezotronics, Inc, Depew, NY) was securely taped to the anteromedial aspect of the distal end of the subject's right tibia. The tape (Elastikon; Johnson & Johnson, Somerville, NJ) was wrapped around the accelerometer and the subject's distal tibia to prevent movement artifacts. All of the subjects wore the same type of neutral racing flat (New Balance, Boston, MA), with a 55-durometer ethylene vinyl acetate midsole. Each subject then warmed up for 5 minutes on a custombuilt treadmill instrumented with 4 force transducers (Frappier Acceleration, Fargo, ND) to measure ground reaction forces. During the warm-up, subjects slowly increased their speed to a self-selected pace, which ranged from 2.4 to 2.6 m/s. At the end of the warm-up period, without the subjects being aware of data being collected, 15 seconds of data were collected from the accelerometer and the force transducers. The accelerometer and force transducer data were collected at 1080 Hz on a laptop computer. The feedback period began immediately after the warm-up period, without alteration in running speed. A custom program written in LabVIEW (National Instruments, Austin,

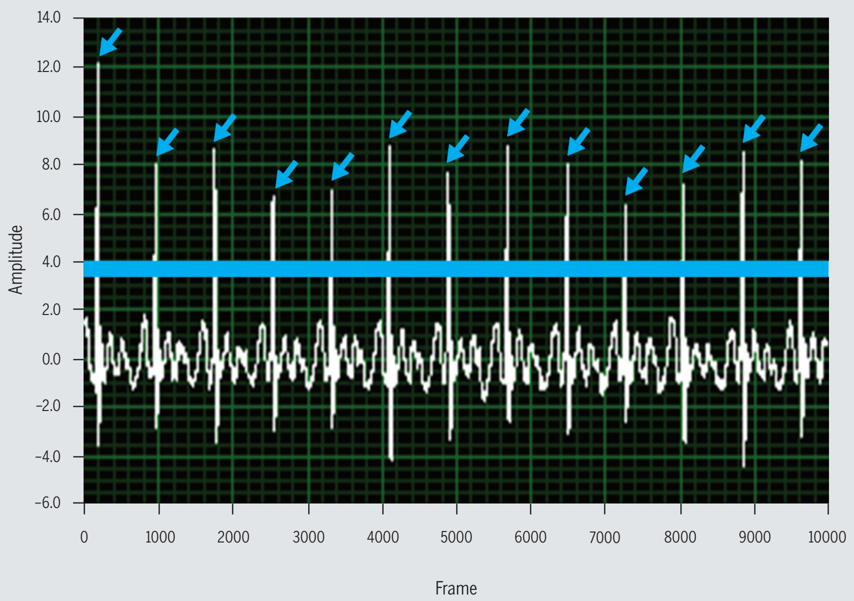

FIGURE 1. Example of real-time feedback of tibial acceleration during running. Arrows identify the peak positive acceleration (PPA) of successive steps with the right foot. Subjects were instructed to maintain their PPA below the horizontal line, indicating 50% of their mean PPA.

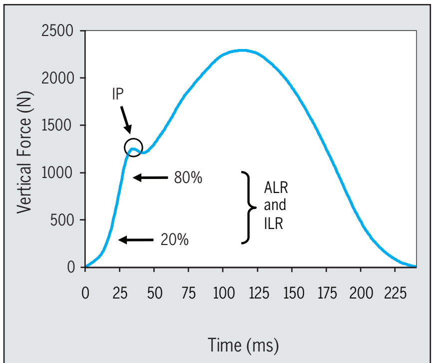

FIGURE 2. Vertical ground reaction force variables. The impact peak (IP) is circled. The average loading rate (ALR) and instantaneous loading rate (ILR) were calculated in the region between 20% and 80% of the IP.

TX) provided continuous real-time visual feedback of the accelerometer signal for the subjects. Real-time visual feedback was used so that the results would not depend on the skill and verbal instructions of the researchers to tell subjects how to reduce their peak tibial acceleration. In addition, visual feedback was selected over auditory feedback so that subjects could see their progress over time, as they worked to reduce their peak tibial acceleration. The accelerometer signal was displayed on a monitor positioned approximately 1 m in front of the treadmill and slightly below the subject's eye level. For each subject, the accelerometer signal was visually inspected, and a mean value of the peak positive acceleration (PPA) was estimated (**FIGURE 1**). A horizontal line was placed across the monitor at approximately 50% of the mean PPA. Preliminary testing at the University of Delaware (unpublished data) showed that some individuals could reduce their tibial acceleration by more than 50%. The 50% goal was set to determine if large changes in tibial acceleration could be achieved during a brief session. Subjects were instructed to run softer and to keep their PPA below the line placed across the monitor. At the end of the 10-minute feedback period, another 15 seconds of accelerometer and force transducer data were collected without the subjects' knowledge. The visual feedback was then removed and the subjects were instructed to continue running with their reduced loading gait pattern. The subjects ran for 10 more minutes without feedback. At the end of the no-feedback period, 15 seconds of accelerometer and force transducer data were again collected without the subjects' knowledge. To end the session, the speed of the treadmill was reduced and subjects cooled down for 5 minutes. There were no interruptions in running between the periods (warm-up, feedback, no-feedback, and cool-down). The total running time for each subject was 30 minutes.

Data Processing

The accelerometer data and the force transducer data were processed using custom programs written in MATLAB (The MathWorks, Inc, Natick, MA). The programs converted the accelerometer and force transducer voltages into units of acceleration due to gravity (g) and Newtons (N), respectively. The accelerometer data were filtered recursively at 100 Hz, with a 4-pole, Butterworth, low-pass filter. The vertical ground reaction force data from the force transducers were filtered at 35 Hz with a recursive, fourth-order, Butterworth, low-pass filter. Next, the accelerometer and vertical ground reaction force data were examined to identify the first 20 steps, with the right foot in each of the three 15-second data collection periods. The data were then processed in a custom LabVIEW program that identified PPA and impact peak (IP). It also calculated average loading rate (ALR), and instantaneous loading rate (ILR). The IP was the local maximum in the vertical ground reaction force that occurred early in stance and was between initial contact and maximum vertical force (**FIGURE 2**). The ALR was calculated as the slope of the line from 20% to 80% of IP (**FIGURE 2**). This is the most linear portion of the vertical ground reaction force curve during early stance phase. The ILR was calculated as the maximum slope between adjacent data points in this linear region (**FIGURE 2**).

Data Analysis

The effects of the feedback provided to the subjects as they ran on the treadmill were evaluated using a single-subject analysis. This type of analysis is used to determine if the intervention (in this case, feedback

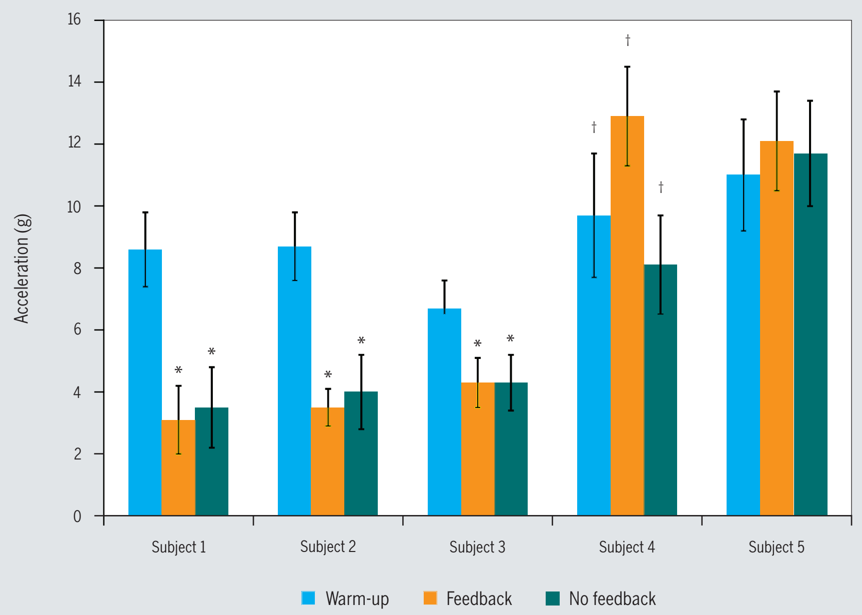

FIGURE 3. Peak positive acceleration (PPA) in units of acceleration due to gravity (g) for each subject during the warm-up, feedback, and no-feedback periods. Error bars represent ±1 SD. *Significantly different from the warm-up period. †Significantly different from each of the other 2 periods.

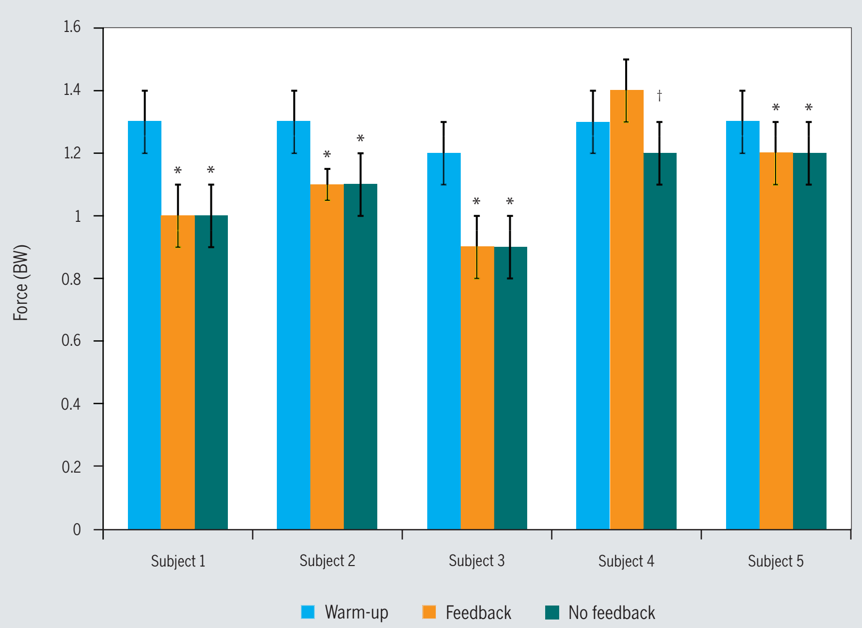

FIGURE 4. Impact peak (IP) as a multiple of body weight (BW) for each subject during the warm-up, feedback, and no-feedback periods. Error bars represent ±1 SD. *Significantly different from the warm-up period. †Significantly different from both the warm-up and feedback periods.

of tibial acceleration) has an effect on an individual subject.[39] In a typical statistical analysis of group data, the effect of an intervention on individuals may be masked.[18] Thus, a single-subject design and analysis are appropriate for examining whether individuals can modify their running mechanics to reduce tibial acceleration. The dependent variables in this study were PPA, IP, ALR, and ILR. In a single-subject analysis, the trial data from a subject are treated as if they were data from a group of subjects in an experiment.[2] For example, in the current study, each of the impacts by the right foot during each 15-second data collection period (warm-up, feedback, and no-feedback) was considered a trial. In addition, each trial in a single-subject analysis is considered to be independent. For each subject, the first 20 trials in each of the data collection periods were used in the analysis. In this case, a repeated-measures analysis of variance (ANOVA) was conducted for the data collected from each subject during the warm-up, feedback, and no-feedback periods. The assumption of independence was checked by examining plots of the standardized residuals.[11] The trial variables were considered random variables, and the Tukey method of pairwise comparisons was used to identify significant differences among the results from each of these periods. The level of significance for all statistical calculations was set at .05. The calculations were made using SPSS for Windows, Versions 15 and 17 (SPSS, Inc, Chicago, IL).

RESULTS

Feedback about tibial acceleration was provided in a standardized manner to all subjects, and there were similarities and differences in their responses to the feedback. Examination of the standardized residual plots confirmed that the trial data were independent for each subject. Subjects 1 and 2 had similar patterns in their responses, with a significant decrease in PPA, IP, ALR, and ILR values after the feedback period, as compared to the end of the warm-up. In addition, they were able to maintain these decreases to the end of the no-feedback period (**FIGURES 3-6**).

Subject 3 also had significant decreases in PPA, IP, ALR, and ILR values by the end of the feedback period (**FIGURES 3-6**). Like subjects 1 and 2, she was able to maintain the decreases in PPA and IP through the end of the no-feedback period. Interestingly, she showed an additional significant reduction in ALR and ILR values by the end of the no-feedback period when compared to the end of the feedback period (**FIGURES 5** and **6**).

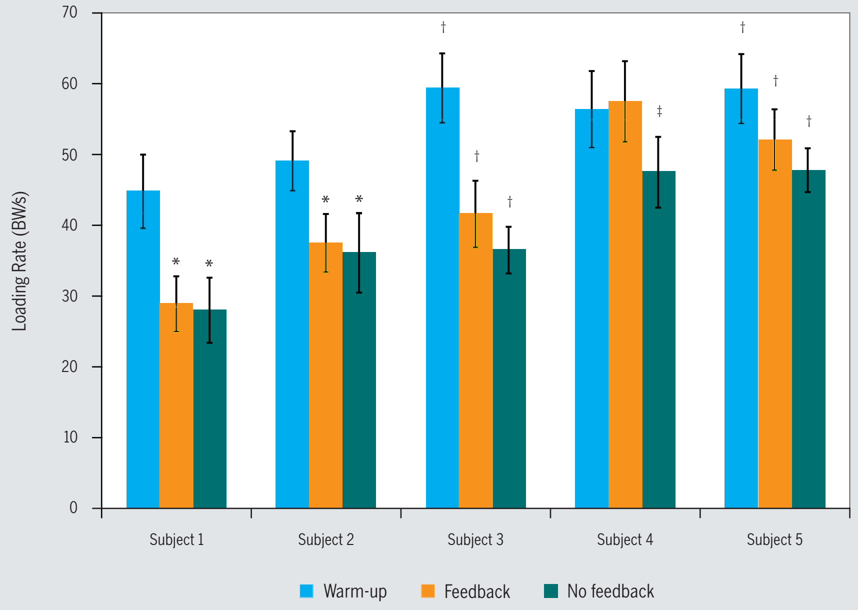

FIGURE 5. Average loading rate (ALR) in body weight per second (BW/s) for each subject during the warm-up, feedback, and no-feedback periods. Error bars represent ±1 SD. *Significantly different from the warm-up period. †Significantly different from each of the other 2 periods. ‡Significantly different from both the warm-up and feedback periods.

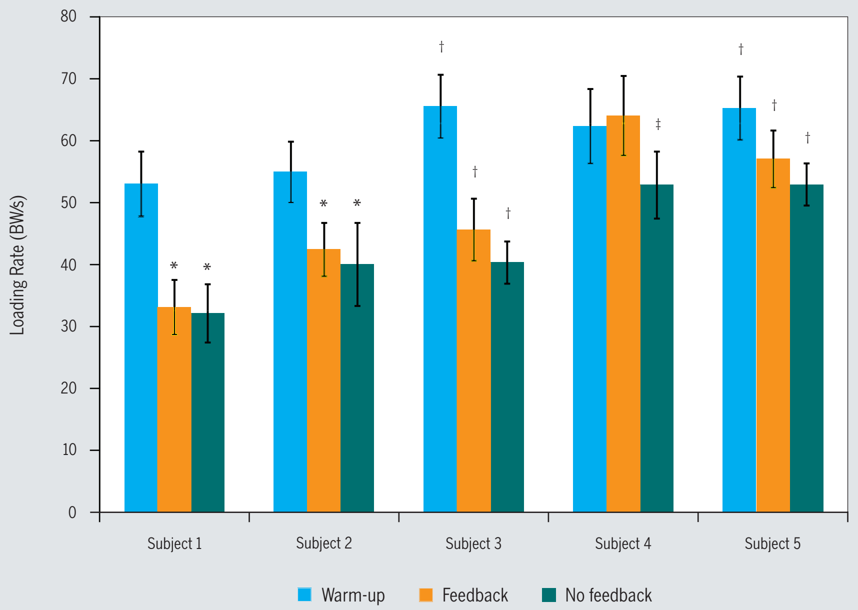

FIGURE 6. Instantaneous loading rate (ILR) in body weight per second (BW/s) for each subject during the warm-up, feedback, and no-feedback periods. Error bars represent ±1 SD. *Significantly different from the warm-up period. †Significantly different from each of the other 2 periods. ‡Significantly different from both the warm-up and feedback periods.

The response of subject 4 to the feedback was very different from the responses of subjects 1, 2, and 3. Subject 4 had increases in PPA, IP, ALR, and ILR values between the ends of the warm-up and feedback periods (**FIGURES 3-6**), which was significant for PPA. However, by the end of the no-feedback period, her PPA, IP, ALR, and ILR were all significantly lower than at the end of the warm-up period (**FIGURES 3-6**).

The response of subject 5 to the feedback was different from that of other subjects with regard to PPA. This subject's PPA values were not significantly different between any of the data collection periods (**FIGURE 3**). However, she reduced her IP values in a pattern similar to that of subjects 1, 2, and 3 (**FIGURE 4**). She also reduced the magnitude of her ALR and ILR values in a pattern similar to that of subject 3 (**FIGURES 5** and **6**).

Another difference in the responses of the subjects to the feedback was the magnitude of the changes in PPA, IP, ALR, and ILR values. The percentage changes in PPA between the end of the warm-up period and the end of the no-feedback period ranged from a 60% reduction for subject 1 to a 6% increase for subject 5 (**TABLE**). The decreases in IP, ALR, and ILR values between the ends of the warm-up and no-feedback periods were large, although not generally as large as the decreases in PPA values. In addition, the decrease in IP, ALR, and ILR values for subjects 1, 2, and 3 were roughly 1.5 to 2 times larger than the decreases achieved by subjects 4 and 5 (**TABLE**).

DISCUSSION

THE PURPOSE OF THIS STUDY WAS TO determine whether runners could reduce their tibial acceleration and ground reaction force loading using real-time tibial acceleration data as visual feedback. In a single session of training, 3 of 5 subjects were able to significantly reduce the magnitude of their PPA while they received feedback. Ten minutes after the feedback was removed, 4 of the 5 subjects exhibited significantly reduced PPA values. In addition, at the end of the no-feedback period, all subjects had reduced IP, ALR, and ILR values compared to those of the warm-up period. These results are similar to those of previous jumping and walking studies, which noted alterations in ground reaction force loading after just a single session of training using various forms of feedback.[7,13,31,35,38] It was encouraging to note that subjects could keep their PPA, IP, ALR, and ILR levels below those recorded at the end of the warm-up period, 10 minutes after the feedback was removed. This suggests that subjects may be able to retain these changes to their running mechanics at least for a brief period.

Some of the subjects responded to the feedback in ways that we expected and others did not. Subjects 1 and 2 responded to the feedback as we expected. During the feedback period, they reduced the magnitude of their PPA, IP, ALR, and ILR. When the feedback was removed, their PPA, IP, ALR, and ILR values stayed at the reduced level (**FIGURES 3-6**). Like subjects 1 and 2, subject 3 reduced her PPA, IP, ALR, and ILR values during the feedback period as expected (**FIGURES 3-6**). However, it appears that she modified her gait further during the no-feedback period. This resulted in an additional significant decrease in ALR and ILR at the end of the no-feedback period, which we did not expect (**FIGURES 5** and **6**). The results presented by subject 4 were quite unexpected. Although it is unclear why her PPA values would increase and then decrease, there are 2 possible explanations. First, she may not have found a strategy to reduce the magnitude of her PPA during the feedback period; however, continued efforts during the no-feedback period seem to have been successful. Alternatively, as the subjects did not know when data were being collected and when the feedback period would end, subject 4 might have been trying an obviously unsuccessful strategy to reduce magnitude of her PPA at the time that the data were collected. Nevertheless, subject 4 was able to reduce her PPA, IP, ALR, and ILR values by the end of the no-feedback period (**FIGURES 3-6**). Subject 5 was apparently unable to find a strategy to modify her gait to reduce the magnitude of her PPA (**FIGURE 3**). However, she was able to reduce the magnitude of her IP, ALR, and ILR at the end of the feedback period (**FIGURES 4-6**). Like subject 3, the additional reductions in ALR and ILR values that subject 5 achieved at the end of the no-feedback period were unexpected (**FIGURES 5** and **6**). The results of subjects 3 and 5 suggest that the gait changes needed to modify IP, ALR, and ILR are not always the same as those needed to modify PPA.

TABLE Percent Change in PPA, IP, ALR, and ILR from the End of the Warm-up Period to the End of the No-Feedback Period for Each Subject

Subject	PPA	IP	ALR	ILR
1	–60*	–24*	–38*	–39*
2	–54*	–16*	–26*	–27*
3	–36*	–30*	–39*	–38*
4	–17*	–10*	–16*	–15*
5	+6	–6*	–19*	–19*

Abbreviations: ALR, average loading rate; IP, impact peak; ILR, instantaneous loading rate; PPA, peak positive acceleration.
** Significant difference between the end of the warm-up period and the end of the no-feedback period ($P<.05$).*

Providing real-time feedback of tibial acceleration may be an effective method to reduce impact loading. Currently, runners use shoes made with shock-absorbing midsoles, or they use shock-absorbing insoles or orthoses to reduce impact loading. Researchers have found that shoes with more cushioning in the midsole can reduce PPA by 11% to 20% compared to shoes with less cushioning in the midsole.[6,27] Similarly, the use of shock-absorbing insoles or orthoses has been found to reduce PPA, IP, ALR, and ILR by as much as 16%, 10%, 18%, and 23%, respectively.[14,32,33] Although the reductions in PPA, IP, ALR, and ILR through the use of shoes or orthoses were significant, subjects 1, 2, and 3 achieved larger reductions through the use of real-time visual feedback of tibial acceleration (**TABLE**). In addition, subjects 1 and 2 had reductions in PPA (**FIGURE 3**) that brought their PPA values within the normal range of PPA, which is roughly 3 to 8 g.[10,16,23,30] For subjects 4 and 5, their PPA values remained above 8 g (**FIGURE 3**), and they did not achieve the same reductions in IP, ALR, and ILR as the other subjects (**TABLE**). It may be that they needed more time to practice with the feedback, because individuals learn at different rates.[15,20] Alternatively, even after further practice with the feedback, subjects 4 and 5 may not have made improvements, and they might need to use shoes with additional cushioning or shock-absorbing insoles to reduce their impact loading. Thus, real-time feedback with tibial acceleration by itself or in combination with shock-absorbing shoes, insoles, or orthoses may be effective in reducing impact loading for runners.

The simplicity of the feedback system used in this study makes it easily adaptable for other environments, requiring only an accelerometer, treadmill, and laptop computer. While it is recognized that high tibial acceleration may not directly cause stress fractures, high PPA, ALR, and ILR have been linked to stress fractures.[10,30] Feedback on any of these variables (ie, PPA, ALR, and ILR) could be provided as part of a gait-retraining program. However, to provide feedback on vertical-force loading rates, a treadmill instrumented with force transducers would be required. These are expensive and not readily available. On the other hand, accelerometers are relatively inexpensive compared to instrumented treadmills, and they are readily available. In addition, tibial acceleration and vertical-force loading rates are strongly correlated.[16,21] Although verbal instruction ("run softer") was provided to the subjects at the beginning of their feedback period on the treadmill, it would probably not be the sole means of feedback for this gait retraining in the future. Augmenting the verbal instructions with real-time visual feedback may have advantages, particularly in settings where many subjects would undergo retraining at the same time. The main advantage of feedback from the accelerometer is that a therapist, trainer, or coach is not required to watch each step by each subject and give feedback. Also, feedback from the accelerometer gives a quantitative indication of the subject's progress. If the retraining program relied solely on verbal feedback, the only quantitative assessment of the subject's performance would come at the posttraining data collection. Therefore, accelerometry provides a feedback method that has the potential for application in a wide variety of settings, such as physical therapy clinics, universities, and fitness centers.

While most of the subjects reduced the magnitude of their PPA, IP, ALR, and ILR as expected, there were some limitations to the methods used in this study. There was no control group, and the data collection at the end of the no-feedback period occurred only 10 minutes after the feedback period. In addition, we did not objectively measure gait kinematics. The lack of a control group raises questions about whether the reductions in PPA, IP, ALR, and ILR are the result of the feedback or fatigue. It is unlikely that fatigue caused the reductions, because fatigue from running on a treadmill at a continuous speed has been found to increase PPA rather than decrease it.[12,42] With regard to the data collection at the end of the no-feedback period, in motor-skill-learning studies the retention test is usually given after a rest period. This is typically hours or days after the training. In the present study, there was no interruption in running on the treadmill after the feedback period, and the retention test was given 10 minutes after the feedback was removed. This is a limitation; however, our primary focus was on determining if subjects could keep their PPA reduced without continuous feedback. Future studies should conduct the retention test many days after the subjects complete the training session. We did not measure gait kinematics because our objective at this time was to determine if subjects could reduce the magnitude of their PPA, IP, ALR, and ILR, not how they did it. While observations did not reveal anything about their gait that looked abnormal either during the warm-up period or anytime after they received feedback from the accelerometer, collection of kinematic data is to be considered in future studies.

In this study, we collected a limited set of data from 5 subjects primarily as a feasibility study. Our goal was to determine if individuals could reduce their tibial acceleration and ground reaction force loading at least for a short period. Future studies should incorporate a larger number of subjects, multiple training sessions, longer follow-up periods, and the use of comparative groups. In addition, kinematic and electromyographic data may be useful to identify changes in gait mechanics and neuromuscular activity. Additional studies could also include measures of energy expenditure and manipulations of the training program.

CONCLUSION

We demonstrated that real-time visual feedback of tibial acceleration can be used by individuals to reduce the magnitude of their PPA, IP, ALR, and ILR when running. Moreover, the subjects maintained these reductions for 10 minutes after the feedback was removed. Continued study of feedback with tibial acceleration to reduce lower extremity loading may lead to training programs that reduce the risk of stress fractures.

KEY POINTS

FINDINGS: Individuals can use real-time visual feedback of tibial acceleration to reduce the loading on their lower extremities while running, and they can maintain the reductions for at least 10 minutes after the feedback is removed.

IMPLICATION: It may be possible to train individuals to run in a way that reduces their risk of stress fractures.

CAUTION: Long-term studies with more subjects are needed to determine if these results apply to a larger population and to determine the persistence of the reductions in loading.

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