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The Relationship Between Landing Sound, Vertical Ground Reaction Force, and Kinematics of the Lower Limb During Drop Landings in Healthy Men

Lower-limb injuries are common among male athletes, accounting for 77% of hospitalized sport-related injuries.[1] High-impact forces are one of the many factors thought to contribute to lower extremity injuries.[20] A prospective cohort study of 1512 nonelite active persons reported that the ankle joint, thigh, and knee joint were the most common sites of injury (38%, 36.5%, and 30.1%, respectively).[25]

In an effort to decrease the prevalence of lower extremity injuries and their associated long-term disability and economic burden,[4,7,17] multiple injury prevention programs have been proposed.[8-11,13,14,21] Several of these programs instruct participants to land softly in an attempt to teach proper landing technique and reduce impact forces.[10,14,21,22] Mandelbaum et al[14] reported an 88% decrease in anterior cruciate ligament injuries in 1041 female subjects using soft landing cues as part of a sports-specific training intervention, compared to 1905 age- and skill-matched females who did not receive the intervention. To date, it is not known whether an audibly quieter landing sound correlates with a decrease in the vertical ground reaction force (vGRF).[20]

STUDY DESIGN: Controlled laboratory study, cross-sectional.

BACKGROUND: Soft-landing instruction, which is advocated in several injury prevention programs, is thought to have a qualitative relationship with decreased vertical ground reaction forces (vGRFs) and increased lower-limb joint excursions.

OBJECTIVE: To quantify the relationships among landing sound, vGRFs, and lower-limb kinematics during a drop-landing task.

METHODS: Twenty-six asymptomatic men aged 18 to 35 years were asked to perform 15 single-leg drop landings from a 30-cm height. Five trials were collected under 3 sound conditions: normal, quiet, and loud. The vGRF, lower-limb kinematics (sagittal plane), and impact sound were recorded during the deceleration phase.

RESULTS: A simple linear regression revealed a significant relationship between landing sound and vGRF (R^2 = 0.42, P<.001). A repeated-measures analysis of variance showed that ankle and knee excursion significantly increased by 7.0° and 11.7°, respectively, during quiet landing (compared to normal landing; P<.001). During the loud landing condition, ankle joint excursion significantly decreased by 9.4° compared to the normal landing condition (P<.001), and hip joint excursion significantly increased by 4.0° compared to normal landing condition (P<.045).

CONCLUSION: As landing sound decreases, so does vGRF during a drop-landing task. These reductions were achieved by increasing ankle and knee joint excursions. Conversely, as the landing sound increases, so does vGRF. This was the result of decreasing ankle joint excursion and increasing hip joint excursion. *J Orthop Sports Phys Ther 2016;46(3):194-199. Epub 26 Jan 2016. doi:10.2519/jospt.2016.6041*

KEY WORDS: *impact force, injury prevention, joint excursion*

A randomized controlled trial by McNair et al[16] reported a 13% decrease in peak vGRF during a drop-landing task when 80 adult recreational athletes were instructed to listen to the sound of their landing. Similarly, peak vGRFs were reduced by 24% in a study in which 12 female recreational athletes were asked to land softly after a maximum vertical jump.[18] Furthermore, peak posterior ground reaction force (GRF) and the knee extension moment at peak posterior GRF were found to be significantly less during a soft landing condition when compared to a natural landing condition during a stop-jump task.[3] Collectively, these studies suggest that a qualitative relationship

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may exist between the sound associated with ground impact and the vGRF.

Research investigating the biomechanics of a drop-landing task under different sound conditions reported a mean increase of 7.5° (9%) in peak knee flexion in 12 female recreational athletes who were instructed to land softly.[18] Additionally, it has been demonstrated that there is a decrease in peak vGRF when participants were instructed to land on the balls of their feet and increase their ankle and knee flexion during drop landings.[18] Furthermore, Tsai and Powers[26] reported a 6% decrease in knee compressive forces after instructing participants to use greater hip and knee flexion during their drop landing. The results of the aforementioned studies suggest that increased joint excursions result in a less impactful landing. While considerable research has investigated the effects of quieter-landing instructions, to our knowledge, no research has explored the effects of a loud landing sound on lower-limb kinematics.

Investigations quantifying the relationship between landing sound and force may have implications in the prevention and rehabilitation of common lower-limb injuries. This relationship may encourage clinicians, coaches, and athletes to use sound as part of their assessment of landing technique and potential injury risk. Furthermore, using landing sound as an assessment tool may prove to be a quick, economical, and simple way to estimate landing forces in the clinical setting.

The purpose of the current study was to investigate the relationship between landing sound and vGRF, and explore the differences in lower-limb kinematics during different landing sound conditions. Based on a review of the relevant literature, it was hypothesized that a reduction in landing sound would be accompanied by a decrease in peak vGRF. Furthermore, it was hypothesized that ankle, knee, and hip joint excursions would increase under a quiet landing condition and decrease during a loud landing condition.

METHODS

Participants

Twenty-six male participants with a mean ± SD age of 21.1 ± 2 years, height of 1.79 ± 0.05 m, and body mass of 78.3 ± 12.2 kg were recruited for the study. Twenty-six participants were required to appropriately power this study with an effect size of 0.3 and an alpha level of .05, utilizing the peak vGRF data of McNair et al.[16] Participants were included if they were male and could speak and understand English. Potential participants were excluded if they had a lifetime history of lower-limb surgery, a 6-week history of lower-limb injury (resulting in missed or modified activity, or treatment from a health care professional), or a severe allergy to tape. Prior to participation, an information sheet and screening questionnaire were provided to each participant. The study was approved by Curtin University's Human Research Ethics Committee, and all participants provided written informed consent.

Instrumentation

Kinetic and kinematic data were collected using a single in-ground force plate (Advanced Mechanical Technology, Inc, Watertown, MA) sampling at 2400 Hz and an 18-camera motion analysis system (Vicon MX; OMG plc, Oxford, UK) sampling at 250 Hz. Sound data were collected at 2400 Hz using a shotgun microphone (ME 66; Sennheiser, Wedemark, Germany) and powering module (K6; Sennheiser) connected to Vicon Nexus software (Version 1.7.1; OMG plc). The shotgun microphone was positioned 300 mm from the center of the force plate (to the right) and 180 mm above the force plate. The right side was chosen for the sound analysis, as only drop landings on the right foot were being examined. Pilot testing revealed that the microphone should be placed as close as possible to the participants' contact foot without interfering with the drop landing. A Rion NL-11 sound-level meter (Rion Co Ltd, Tokyo, Japan) was positioned 20 mm laterally from the microphone. Three recordings of a standardized sound amplitude of 94.1 dB provided by the sound-level calibrator (Rion NC-73; Rion Co Ltd) were collected by the microphone to enable calibration from voltages to decibels (see below for details).

Procedure

Data collection took place at the Curtin University Motion Analysis Laboratory. Upon arrival, participants were given a participant information sheet, signed a consent form, and filled out a screening questionnaire. Measures of each participant's body mass (kilograms) and height (meters) were then obtained using scales and a stadiometer, respectively. In accordance with the Plug-in-Gait[12] kinematic model requirements, left and right lower-limb length, foot length, ankle width, knee width, shoulder offset, elbow width, and hand width were obtained using an anthropometer. Twelve-mm retroreflective markers were fitted to the participants in accordance with the Plug-in-Gait full-body marker set.[12] Participants were then required to complete a 10-minute standardized warm-up that included running and jumping tasks to familiarize themselves with the laboratory setting and presence of the reflective markers. A static trial in the anatomical position was collected for each participant for Vicon marker calibration.

A series of barefoot drop landings onto the force plate were then collected. Participants were asked to "hop off the right foot with the left foot in front and slightly flexed, landing on the right foot" from a height of 30 cm. This jump height was chosen based on previous research suggesting that it was not dissimilar to that commonly encountered during activities of work, sport, and leisure.[16] Participants were given a demonstration and the opportunity to practice the task.

Initially, the participants were instructed to perform drop landings (with no instruction) to obtain a baseline,

normal sound amplitude of landing. The participants were then instructed to remember the sound from this landing and create a quieter or louder sound from this normal landing condition. Instructions were modified from McNair et al,[16] whereby participants were asked to "perform the task as before but this time listen to the sound of your landing and try to make a quieter/louder sound as you land." The normal landing condition always was performed first, and the order in which quiet and loud landing conditions were performed was randomized using the flip of a coin. The performance of the drop-landing task was repeated 5 times for each sound condition, with a 1-minute rest period after each condition to minimize the influence of fatigue.

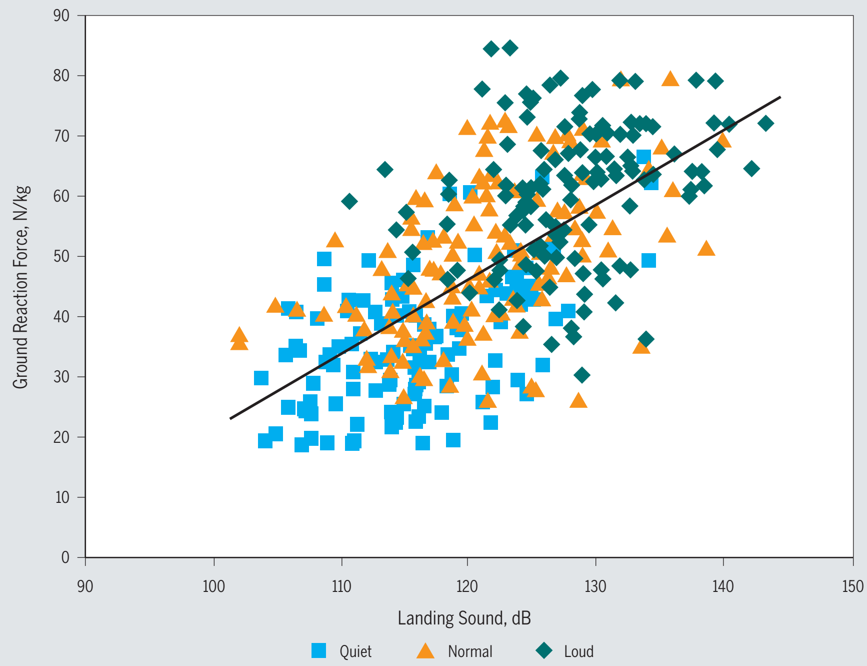

FIGURE 1. The relationship between landing sound and vertical ground reaction force when participants were asked to land with quiet, normal, and loud landing sounds (n = 379).

Data Management

Anthropometric data were entered into Vicon Nexus software. The kinematic data were labeled, trimmed, and checked for breaks that occurred as a result of marker occlusion. A built-in spline interpolation function within Vicon was applied to correct breaks of 15 frames or fewer. All trajectories were visually inspected after spline interpolation to ensure that breaks were filled correctly. A Woltering filtering routine, at an optimal frequency determined using a residual analysis algorithm (LabVIEW; National Instruments Corporation, Austin, TX), was then performed. The Plug-in-Gait model (OMG plc) was then applied to derive the relevant lower-limb kinematic data. A custom-written program developed in LabVIEW Version 2011 SP1 was used to convert the sound data from voltage (V) to sound intensity (dB) by using the equation dB = 20log(V2/V1), where V1 is the root-mean-square of the voltage recorded for the 94.1-dB standard and V2 is the peak voltage recorded by the microphone during the deceleration phase of landing (initial contact with the force plate and maximum knee flexion).[24] A second custom-written LabVIEW program was used to output the sound amplitude, peak vGRF, and peak ankle, knee, and hip excursions during the deceleration phase.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics for Windows Version 22 (IBM Corporation, Armonk, NY). All drop landings were considered independent landing trials, as they produced different sounds and vGRFs. Outliers were identified using box-and-whisker plotting. In total, 11 of 390 trials were removed due to technical errors such as marker occlusion. A Kolmogorov-Smirnov test was used to determine that the vGRFs during drop-landing trials were normally distributed. Descriptive statistics of the sound amplitude in the 3 different sound conditions were performed. A simple linear regression was utilized to determine the relationship between peak landing sound and peak vGRF.

Joint excursions were determined by subtracting the maximum joint angle at the end of the deceleration phase from the joint angle at initial contact. Mean joint excursions of the 5 drop landings for each participant (n = 26) from each sound condition were calculated and assessed for normality using the Shapiro-Wilk test. Data were found to be normally distributed; therefore, a repeated-measures analysis of variance (ANOVA) was utilized to assess for differences in joint excursions between the 3 sound conditions (quiet, normal, and loud). A separate ANOVA was performed for the ankle, knee, and hip joint excursions. If the ANOVA revealed significant differences, post hoc pairwise comparisons using a Bonferroni adjustment were performed to identify which sound conditions exhibited significant differences. The alpha level was set to $P<.05$ for all analyses.

RESULTS

Decibels Versus vGRF

For the total sample of 379 drop landings, the mean sound amplitudes for quiet, normal, and loud landing conditions were 116.0 ± 6.6, 121.4 ± 7.0, and 128.1 ± 6.3 dB, respectively.

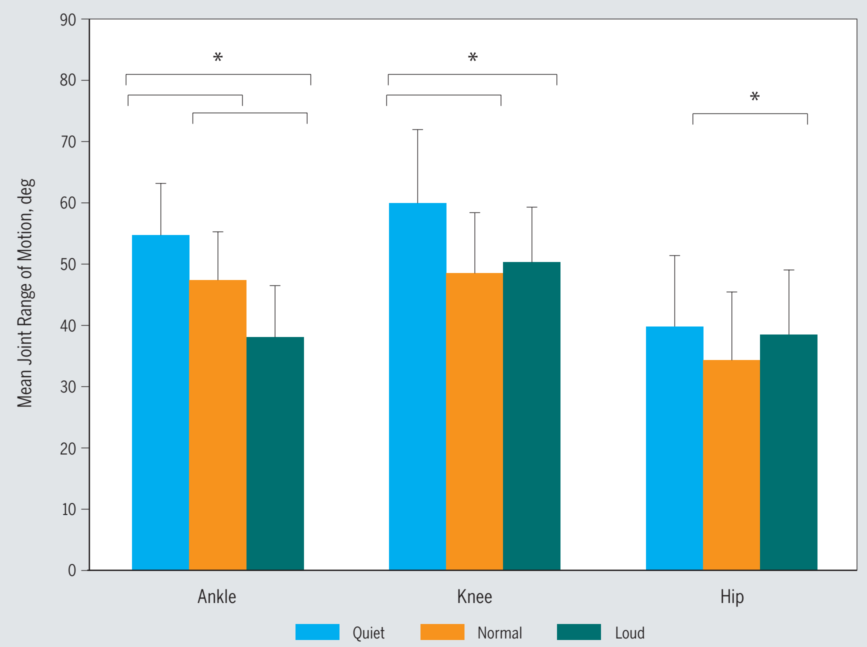

FIGURE 2. Mean ankle, knee, and hip joint excursions when participants were asked to land with quiet, normal, and loud landing sounds. *Denotes statistical significance.

The ranges of the sound amplitudes for the quiet, normal, and loud landing conditions were 103.7 to 134.4 dB, 102.1 to 140.0 dB, and 110.7 to 150.0 dB, respectively. The peak landing sound was found to significantly predict peak vGRF (r = 0.648, P<.001) (**FIGURE 1**).

Ankle Range of Motion

There was a significant main effect for ankle excursion across the 3 different sound conditions (n = 26; $F_{2,50}$ = 94.6, P<.001). Pairwise comparisons revealed that quiet landings resulted in significantly greater ankle excursions than normal landings (mean difference, 7°; P<.001) (**FIGURE 2**, **TABLE**). Normal landings also resulted in significantly greater ankle excursions compared to loud landings (mean difference, 9.4°; P<.001) (**FIGURE 2**, **TABLE**), and quiet landings resulted in significantly greater ankle excursions than loud landings (mean difference, 16.3°; P<.001) (**FIGURE 2**, **TABLE**).

Knee Range of Motion

The repeated-measures ANOVA demonstrated a significant main effect for knee excursion across the 3 different sound conditions (n = 26; $F_{2,50}$ = 22.2, P<.001). Post hoc tests revealed significantly greater knee excursions during quiet landings when compared to normal landings (mean difference, 11.7°; P<.001) (**FIGURE 2**, **TABLE**). Significantly greater knee excursion during quiet landings when compared to loud landings also was seen (mean difference, 9.7°; P<.001) (**FIGURE 2**, **TABLE**). No significant difference in knee excursion was detected between normal landings and loud landings (**FIGURE 2**, **TABLE**).

Hip Range of Motion

A significant main effect for hip excursion was detected across the 3 different sound conditions (n = 26; $F_{2,50}$ = 4.2, P = .021). Pairwise comparisons revealed significantly lower hip excursions during normal landings compared to loud landings (mean difference, –4°; P = .045) (**FIGURE 2**, **TABLE**). No significant differences were observed in hip excursion between the quiet landings and normal landings, nor between the quiet and loud landing conditions (**FIGURE 2**, **TABLE**).

DISCUSSION

The results of our study revealed a significant, linear relationship between landing sound and vGRF during a drop-landing task. Specifically, as landing sound decreased, so did vGRF. It should be noted, however, that the landing sound only explained 42% of the variance seen in vGRF. Consistent with previous research, the quiet landing condition resulted in greater ankle and knee excursions,[3,16,23] while the loud landing condition resulted in decreased ankle joint excursions and increased hip joint excursions compared to the normal landing sound condition.

Measurement of the landing sound across the 3 landing conditions revealed a linear relationship between landing sound and force. Our findings are somewhat supported by previous research that has reported significantly reduced GRF with soft-landing instruction[3,16,23]; however, due to the absence of landing sound measurement in these studies, a quantitative relationship had not been previously confirmed. Decreased GRFs, and the expected associated decrease in joint compressive forces, have clinical significance for the rehabilitation of several lower-limb injuries, such as stress fractures and tendinopathies, that require load modification as part of their management.[2,6] Other authors also suggested that lowering joint forces may limit the progression of joint degeneration in persons with osteoarthritis.[19]

The findings of the current study demonstrate that quiet-landing instruction results in significantly greater joint excursion at the ankle and knee when compared to a normal landing sound instruction. This also is consistent with previous literature that observed significant increases in lower-limb excursions with soft landing sound instruction.[18,26] It is postulated that the increase in joint excursion occurs as participants cushion the impact to decrease the sound of their landing. While it is apparent that an increase in joint excursion during a quiet

landing reduces force and is therefore potentially protective of injuries,[20] increased joint excursions may increase the risk of injury by increasing the muscle demand required to control the additional motion. Further research is needed to determine whether injury prevalence decreases with quieter landings, or whether there is a change in the type of injury. Nevertheless, the use of landing sound as a feedback tool may assist individuals in decreasing joint compressive forces. Furthermore, the identification of the relationship between landing sound and force provides support for injury prevention programs that advocate for soft landings.[10,14,21]

Purposeful loud landings have revealed that the ankle joint, in accordance with the study's hypothesis, displayed significantly less excursion during a loud landing compared to a normal landing or quiet landing. However, contrary to the hypothesis, the hip joint exhibited significantly more excursion during a loud landing when compared to a normal landing, while the knee joint displayed no significant differences between the normal and loud landing sound conditions. This suggests that while the ankle stiffens during a loud landing, the hip moves through a larger excursion to potentially absorb the larger force associated with a loud landing.[5] Therefore, an individual with a naturally loud landing sound (perhaps due to individual technique or the effects of fatigue) may see greater reductions in force if instructed to land with greater ankle excursion as opposed to greater hip and knee excursion.

As mentioned above, the relationship between landing sound and force carries clinical significance due to the inherent connection between high GRFs and lower extremity injury.[15,20] Using landing sound as a feedback mechanism provides a cost-effective, simple way for clinicians, coaches, and athletes to decrease vGRFs and therefore potentially decrease the prevalence of lower-limb injuries. Furthermore, the ability to estimate ground reaction force using only a measured landing sound also may prove to be a valuable tool, particularly with the limited availability of force assessment equipment, both due to cost and practicality. However, further research investigating the relationship between landing sound and force on different surfaces is necessary. Future research should be conducted to determine whether microphones within smart devices have the ability to reliably record landing sound, excluding background noise and other external factors. This could potentially result in the development of a smartphone application that is able to estimate vGRF by recording landing sounds on specific surfaces.

It should be acknowledged that there are many factors that can potentially influence injury, and vGRF is just one variable. Further investigation is required to examine the relationships among sound, vGRF, and other factors during more complex locomotive tasks. For example, a systematic review has demonstrated that vertical loading rate is believed to be more strongly associated with some types of lower-limb injuries than vGRF during running.[27]

Despite the limitations of a study performed only on healthy male individuals, the results presented indicate that a significant, linear relationship exists between landing sound and GRFs during barefoot drop landings onto a force-plate surface. The highly variable nature of human movement may result in different landing sound amplitudes with no accompanying change in force; however, task familiarization prior to data collection and multiple trials of the simple drop-landing task ensured that a consistent sample was obtained under each sound condition to acquire a participant's average landing sound. It is unknown whether our results are applicable to females and to different landing surfaces. An additional limitation of this research was that the participants were not blinded to the aim of the study. Therefore, some participants might have intentionally altered their landing technique during the different sound conditions. However, the partici-

TABLE MEAN ANKLE, KNEE, AND HIP JOINT EXCURSION DURING DROP LANDING ACROSS 3 DIFFERENT SOUND CONDITIONS (QUIET, NORMAL, LOUD; N = 26)

	Mean Difference, deg*	SE	*P* Value
Ankle			
Quiet versus normal	7.0 (4.1, 9.8)†	1.1	<.001
Normal versus loud	9.4 (6.4, 12.3)†	1.1	<.001
Quiet versus loud	16.3 (13.0, 19.7)†	1.3	<.001
Knee			
Quiet versus normal	11.7 (6.5, 16.8)†	2.0	<.001
Normal versus loud	−2.0 (−6.3, 2.3)	1.7	.741
Quiet versus loud	9.7 (4.8, 14.5)†	1.9	<.001
Hip			
Quiet versus normal	5.2 (−0.2, 10.6)	2.1	.064
Normal versus loud	−4.0 (−8.0, −0.1)†	1.5	.045
Quiet versus loud	1.2 (−3.8, 6.1)	1.9	1.000

Abbreviation: SE, standard error.
**Values in parentheses are 95% confidence interval.*
†Denotes statistical significance.

pants were not aware that the investigators were anticipating a decrease in forces when a quiet landing was performed, and the landing instructions given only pertained to sound and had no mention of force. Therefore, it is not anticipated that the lack of blinding influenced our results.

CONCLUSION

The results of this study revealed a linear relationship between landing sound and force during drop landings in a healthy male population. Quieter landings were associated with decreased vGRFs and increased ankle and knee excursion. Louder landings resulted in increased vGRFs, decreased ankle excursions, and increased hip excursions. These results need to be verified in other patient populations. ◉

KEY POINTS

FINDINGS: A linear relationship exists between landing sound and vGRF. Instructing a subject to land quietly resulted in less vGRF and greater ankle and knee range of motion, while loud-landing instruction resulted in increased vGRF, decreased ankle range of motion, and increased hip range of motion.

IMPLICATIONS: Our findings lend support to the concept that quiet-landing instruction may decrease impact forces. The ability to decrease impact forces may have implications in the prevention and rehabilitation of lower extremity injuries.

CAUTION: Only asymptomatic male participants performing barefoot landings onto a force-plate surface were studied.

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