

High impact forces in skateboarding landings affected by landing outcome

Jeremy J. Determan^a, Edward C. Frederick^{bc*}, Joseph S. Cox^a and Matthew N. Nevitt^a

^aSole Technology Institute, 20162 Windrow Dr, Lake Forest, CA 92630, USA; ^bExeter Research, Inc., 80 Haigh Road, Brentwood, NH 03833, USA; ^cUniversity of Massachusetts, Department of Kinesiology, Amherst, MA 01003 USA

(Received 17 November 2009; final version received 16 September 2010)

Purpose. Despite concerns elicited by the injury-rate statistics for skateboarding, the literature has been silent on biomechanical factors that might be causing or exacerbating these injuries. To help fill this void, we sought to describe the kinetic characteristics of landing from a rail slide, one of the more high-risk, albeit common, maneuvers practiced by skateboarders. **Methods.** Twelve top-amateur or professional skateboarders ($BW = 688 \pm 89$ N) performed rail slide maneuvers down a steep handrail before landing on a force plate. We recorded ground reaction force (GRF) data whether the subjects landed successfully (L) on their skateboards, or, bailed-out (BO), i.e. landed on their feet. **Results.** Vertical GRF (VGRF) during L had an initial peak, due to skateboard contact, immediately followed by a set of impact peaks (mean = 7.98 ± 1.32 (SD) BW) representing landing on the board. BO showed a VGRF impact peak rising to a significantly higher ($P < 0.05$) mean of 12.09 ± 2.63 BW. **Conclusions.** These data suggest that the skateboard provides significant shock attenuation. However, because BO landings are frequent, the relatively high peak ground reaction forces are a cause for concern. Given the musculoskeletal immaturity of typical skateboarders, clinicians should be aware of these high impact forces, and footwear manufacturers should explore ways to reduce peak pressures, and high impact and shear forces in the heel, forefoot, and toe box.

Keywords: biomechanics; fall; injury; jump; kinetics; sport

Introduction

In 2006, skateboarding had over 11 million participants in the US alone, putting it on par with or ahead of baseball, football, and tackle football in terms of participation levels in the US (SGMA 2007). Compared with the prior year skateboarding participation levels grew by 5.2%, making it one of the growing sports segments in the US (SGMA 2007). As participation levels in skateboarding have increased, the skill level of the participants involved and complexity of the maneuvers they perform have also increased, leading to the increased opportunity for these athletes to suffer acute and chronic injuries.

Published epidemiological studies characterize skateboarding as a generally safe activity but with a significant and increasing incidence of musculoskeletal injuries to the extremities (Osberg *et al.* 1998, Kyle *et al.* 2002). These papers and other clinical reports published over the last 35 years (Shuman 1967, Jacobs and Keller 1977) describe a wide array of musculoskeletal injuries with a disproportionately high incidence of ankle injuries, and a distressing incidence

of fractures to the foot and ankle. Similar types of acute foot and ankle injuries have been reported in sports activities such as snowboarding, gymnastics, and ballet (Kirkpatrick *et al.* 1998, Ardent and Kerschbaumer 2003, Kirialanis *et al.* 2003, Valderrabano *et al.*, 2005).

Despite the concern elicited by these troubling statistics the literature has been silent on the biomechanical factors that might be causing or exacerbating these injuries. To rectify this gap in the literature, we undertook this investigation to describe the biomechanical characteristics of one of the more high-risk, albeit common, maneuvers practiced by skateboarders.

We report, herein, a study of the so-called *rail slide* maneuver and our analysis of the kinetic consequences of different landing outcomes performed by top-level skateboarders. A rail slide is a popular maneuver practiced by experienced skateboarders. The skater rolls toward the top of a flight of stairs with a handrail, uses a special maneuver called an “Ollie” (Frederick *et al.* 2006) to leap, skateboard and all, onto the handrail, and then rides the skateboard down the

*Corresponding author. Email: ned@exeter-research.com

handrail using the belly or axles of the board to slide along the length of the rail. As skaters approach the end of the rail they rotate their bodies and boards to position themselves for landing. Although they become slightly separated during the airborne phase, a skilled skater will land on top of the skateboard as it hits the ground and ride away. If the skater loses his or her balance while sliding down the rail, they may quickly decide to jump off the board and land on their feet. In the jargon of skateboarding, this is known as a *bail-out*.

We were curious about how large the ground reaction forces might be when a skater successfully lands (L) on the board versus when they land on their feet in a bail-out (BO) situation. We hypothesized that the skateboard would provide significant shock absorption and, therefore, that bail-outs would result in higher impact forces. Our results provide a descriptive record of the kinetics of successfully landing versus bailing out from a rail slide and suggest that the sprung elements of the skateboard do indeed provide significant shock attenuation and, along with adjustments in the pattern of movement, offer the skateboarder some protection from the inevitable effects of gravity.

Methods

Twelve healthy, male, top-amateur and professional skateboarders (mean mass = 70.2 kg, SD = 9.1 kg; mean age = 18.9 years, SD = 3.96 years) participated in this study. Five of our 12 subjects rode “regular” footed, meaning their left foot was placed at the front of the board. Conversely, skateboarders with their right foot placed at the front of the board are considered “goofy” footed. This distinction was important when examining our shear ground reaction force data during the successful landing trials. Prior to testing, subjects read and signed an informed consent form, which was approved by the institutional review board, and details concerning the experiment were explained to them. The experimental setup was constructed to mimic a real-life, street skateboarding setting and the maneuvers we asked our subjects to perform were consistent with the maneuvers they were accustomed to practicing on a daily basis.

Subjects began the trials by rolling across a flat 8.84 m (348 in) platform 1.20 m (47.3 in) above the laboratory floor. At one end of the platform was a gradually sloping, 19° (from horizontal) *roll-in* ramp used by the subjects to build up the horizontal approach speed they needed for the jump. The top of the roll-in ramp was approximately 1.05 m (41.3 in) above the surface of the platform. Due to the relative

complexity and dangerous aspect of the movement, each individual subject was allowed to pick an appropriate approach speed that felt comfortable to them. At the other end of the platform was a set of stairs which contained a 62° (from horizontal) sloping handrail. This structure is similar to what would be known to skaters as an eight-stair handrail. Subjects were required to ollie up onto and slide down the handrail on their skateboards before eventually leaving the handrail and landing on a force plate located approximately 0.483 m (19 in) away from and 0.902 m (35.5 in) below the bottom end of the handrail. Figure 1 shows a diagram of the experimental setup. Relative to the orientation of the diagram in Figure 1, the subjects traveled from right to left during all of the trials.

A large AMTI model BP12001200 force plate (1.2 m long and 1.2 m wide) was used to measure ground reaction forces (Advanced Mechanical Technologies, Inc., Newton, MA, USA). Force data for all components were collected at 1000 Hz and low-pass filtered using a fourth-order Butterworth filter with a 100 Hz cutoff frequency which was determined after examining the power spectral density of the three signals. Prior to analysis, force data were normalized to weight for across subject comparison purposes. All ground reaction force data were analyzed after a threshold of 25 N in the vertical signal was reached using a custom written Matlab program. Shear forces were collected and described by an orthogonal coordinate system defined by the direction of motion of the skateboard/subject system. During BO trials, anterior–posterior (AP) and medial–lateral (ML) forces were used to describe the forces acting upon the subjects’ bodies as their feet came in contact with the force plate. During the L trials though, when the subject’s body was positioned on top of the skateboard and oriented perpendicular to the direction of motion, the shear forces were used to describe the forces acting on the skateboard. This means, reported ML forces during the L trials refer to the forces acting on the overall system even though the subjects were actually rocking back and forth anteriorly (toe-side) and posteriorly (heel-side) to stabilize themselves on top of their boards during landings. Similarly, even though the subjects were actually applying slight ML body movements to stabilize themselves on top of their boards during landings, reported AP forces during the L trials refer to the braking and propulsive forces of the skateboard/rider system as it landed on the force plate.

To provide a visual aid to help us interpret the kinetic data, high speed video was captured at 240 Hz using a high speed digital video camera (model: JVC GRL-9800). It was viewed using a special digital video

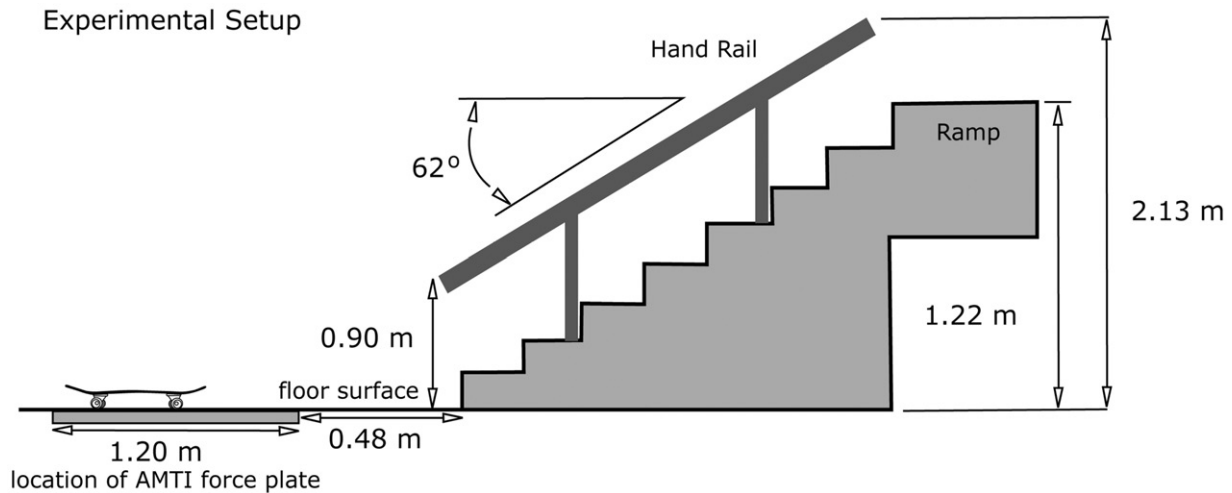


Figure 1. Diagram of the experimental setup. The bottom of the handrail to the right was raised 0.90 m above the floor surface. The 1.20 m long AMTI force plate was mounted flush with the floor with its farthest edge approximately 0.48 m from the edge of the stairs. Subjects traveled from right to left.

software program (Biomechanica LLC, Portland, OR, USA). In addition, in-shoe pressure sensors (RSscan INTERNATIONAL®, Olen, Belgium) were placed in both shoes to provide qualitative visual data on the distribution of forces under the surface of each foot. The pressure data were captured at 500 Hz on a data-logger with a removable 4-MB SRAM PCMCIA card carried in a waist pack. After each trial, the pressure data were transferred from the PCMCIA card to a desktop computer for subsequent analysis using the RSscan software.

Each subject used their own skateboard. Across all of our subjects; skateboard trucks and wheels as well as deck length, width, stiffness, and concavity differed dramatically based on the personal preferences of the rider. Therefore, to minimize the chance of hindering their performance and risking injury due to the relatively dangerous maneuver performed by them, the subjects were allowed to use their own skateboards during the study. However, all subjects were required to wear the same model of skateboarding shoe (Model: *és EK 01*), in their size, during the study. The shoe was chosen because of its popularity amongst skateboarders and its construction, which was typical of modern skate shoes. The shoes were of a basic double-cupsole style of construction with a layer of ethylene vinyl acetate (EVA) foam functioning as a polymeric foam midsole. The polymeric foam layer was 16 mm thick in the heel area; tapering to 8 mm thick under the ball of the foot. Underneath the heel region of the midsole there was a 6-mm thick slab of a viscoelastic gel-like material sitting atop 10 mm of EVA foam.

We recorded data on all cases of landing whether the subjects landed successfully (L), i.e. landed on their skateboard with all four wheels completely hitting the force plate, or, bailed-out (BO), i.e. they became separated from their skateboard in mid-air and landed with both feet fully on the force plate. Subjects were instructed to approach each jump with the intent of successfully landing on their skateboard, that way BO trials were natural and considered a random unsuccessful outcome. Because of the elite professional or top-level amateur status of the subjects used in this study, L trials were far more frequent than BO trials which usually occurred more often later on in the study when the subjects had warmed up and were trying more difficult tricks on the stair handrail. Due to the precarious and violent nature of the BO landing conditions and the fact that our subjects were considered top professional or top up-and-coming amateurs in the sport, we only collected a maximum of three good BO trials for each subject, before asking them to stop, to reduce the chances of injury.

To examine the potential role of the skateboard in providing significant shock attenuation during landings, three L trials were randomly selected from the multiple L trials to compare against the three BO trials within each subject. We conducted a repeated measure one-way ANOVA ($\alpha=0.05$) using the 12 mean maximum vertical impact force values calculated from each subject during the L and BO trials. Shear force values were also reported for each landing outcome, but were not statistically compared.

Results

Landing on the skateboard seems to provide significant ($P < 0.05$) peak impact force reduction during landings. Mean maximum vertical impact forces were found to be 8211.7 N (12.09 BW) during bail-outs compared to 5344.3 N (7.98 BW) during successful landings. Results for all the maximum GRF data for each subject can be found in Table 1.

The L vertical ground reaction force (VGRF) data for all three trials for a single, representative subject (Subject 1) can be found in Figure 2. As the board landed on the force plate and the full weight of the subject landed on top of the board, two sets of impact and one set of active peaks occurred. The first initial set of landing peaks (LP1) corresponded with the initial contact of the board landing on the force plate and the plantar flexed forefoot of the skater coming in contact with the board. These preliminary peaks were usually lower in magnitude (approximately 2–4 times BW) and occurred within the first 10–30 ms of contact. A single LP1 occurred when the board came down in a flat position (i.e. all four wheels contacted the ground at relatively the same time), whereas two peaks occurred if the board came down slightly off axis where one side of the board's wheels contacted the ground before the other side. 40 to 50 milliseconds after the initial impact peaks, the L VGRF rose rapidly in magnitude to greater impact peak (LP2) as the full weight of the skater's body landed on the board. Shortly after LP2, a secondary set of active landing peaks (LP3) occurred as the skateboarders stabilized themselves on the board. These active peaks usually composed of one or two secondary peaks occurring 50 to 75 ms after initial contact. The mean maximum VGRF for all of the subjects including all of the trials for the L condition was 5344.3 ± 629.5 N or 7.98 ± 1.32 BW (Table 1). In approximately five of our 12 subjects the magnitude of LP2 was consistently one to three BW greater than LP3. In three of the subjects LP3 was, on average, larger in magnitude than LP2. Four of the subjects exhibited both types of landing patterns. In-shoe pressure results showed that most of the force was being borne by the forefoot region of the front foot, particularly across the first through third metatarsal heads and up to the hallux, as well as the medial side of the back foot during the time these larger magnitude force peaks were occurring.

The ML GRF and the AP GRF results for the L condition were quite variable both within subjects and between subjects (Figures 2 and 3). The only regular feature of the medial–lateral force we can report is that the sinusoidal shape of the curves

seemed characteristic of an oscillation: an expected result given the nature of stabilizing body movements. Mean heel side GRF forces (MLhs) during the landing trials were found to be 952.9 ± 169.0 N or 1.39 ± 0.25 BW, while mean toe side GRF forces (MLts) were found to be 562.6 ± 218.0 N or 0.82 ± 0.32 BW. Anterior–posterior GRF results for the L condition were found to be relatively minimal due to the fact the wheels on the skateboard were free to roll upon landing. Mean braking AP GRF forces during the landing trials were found to be 496.3 ± 260.3 N or 0.74 ± 0.41 BW, while mean propulsive AP GRF forces were found to be 51.9 ± 32.4 N or 0.08 ± 0.05 BW (Table 1).

When a bail-out occurred and subjects landed on their feet, significantly larger forces were recorded. Figure 4 contains the BO data for all three trials for a single representative subject (Subject 3). In most trials two or three sets of impact peaks were present. The first of these peaks consisted of a preliminary lower magnitude impact peak (BOP1) occurring 15–25 ms after initial impact signifying the forefoot of the skater's lead foot making contact with the force plate. This preliminary peak was then followed by one or two secondary peaks depending on the way the skater landed on the force plate. As seen in other jump landing studies (Valiant and Cavanagh 1985, Stacoff *et al.* 1988), most of the skaters in our study landed on the force plate with their feet in a plantar flexed position with one foot slightly ahead of or in front of the other causing two distinct peaks (BOP2 and BOP3) occurring 35–40 and 60–70 ms after initial contact. In some trials though, both feet landed simultaneously at the same time and only a single secondary impact peak was present (see Figure 5). The magnitude of the largest of these secondary bail-out impact peaks had a mean value of 8212 ± 1615 N or 12.1 ± 2.63 BW across all the subjects and trials (Table 1). In shoe pressure data showed that at the moment these peak impact forces were occurring most of the force was primarily being applied to the heel region of the foot during bail-out landings.

The ML GRF and AP GRF results for the BO conditions were quite variable both within subjects and between subjects (Figures 4 and 5). Average medial–lateral peaks ranged from -722.9 ± 495.0 N or -1.07 ± 0.76 BW in the medial direction to 1036.1 ± 606.3 N or 1.49 ± 0.80 BW in the lateral direction. The mean peak value of the braking force in the AP data was also found to be rather large across all subjects and trials at 2444 ± 608 N or 3.62 ± 1.07 BW (Table 1).

Table 1. Peak ground reaction forces during the Landing (A) and Bail-Out (B) conditions in Newtons and in body weights. Individual means and standard deviations include three trials per subject. All results are in Newtons of force and normalized to the subject's body weight. V_{\max} indicates the peak vertical GRF. ML_{\min} and ML_{\max} indicate GRF maximum and minimum values in the Fx or medial-lateral plane. AP_{\min} and AP_{\max} indicate GRF maximum and minimum values in the Fy or anterior-posterior plane. For reference, subject body weights are shown in the rightmost column.

		Bail Out Forces in Newtons (N)					Bail Out Forces in Body Weights (BW)					Body Weight
A:		V_{\max}	ML_{ts}	ML_{hs}	AP_{\min}	AP_{\max}	V_{\max}	ML_{ts}	ML_{hs}	AP_{\min}	AP_{\max}	BW (N)
S1	Mean	5894.2	530.8	1069.2	-49.4	716.8	10.01	0.90	1.82	-0.08	1.22	588.7
	SD	342.4	401.0	255.9	19.9	180.8	0.58	0.68	0.43	0.03	0.31	
S2	Mean	3657.6	437.1	709.4	-25.0	234.8	6.21	0.74	1.21	-0.04	0.40	588.6
	SD	47.9	66.0	98.9	11.9	112.3	0.08	0.11	0.17	0.02	0.19	
S3	Mean	5431.1	171.2	1037.3	-49.1	1108.1	8.25	0.26	1.58	-0.07	1.68	658.3
	SD	847.3	111.0	451.8	38.1	153.5	1.29	0.17	0.69	0.06	0.23	
S4	Mean	5517.6	555.9	1113.7	-23.4	602.1	6.89	0.69	1.39	-0.03	0.75	810.1
	SD	603.8	232.7	258.8	9.5	151.0	0.75	0.29	0.32	0.01	0.19	
S5	Mean	6097.2	671.9	1094.4	-26.8	469.6	8.56	0.94	1.54	-0.04	0.66	712.2
	SD	302.7	250.7	186.2	16.4	20.6	0.43	0.35	0.26	0.02	0.03	
S6	Mean	5695.5	409.9	1066.9	-138.9	762.6	8.83	0.64	1.65	-0.22	1.18	645.3
	SD	900.5	287.8	166.8	151.2	17.9	1.40	0.45	0.26	0.23	0.03	
S7	Mean	5691.7	896.1	983.2	-62.8	331.3	7.44	1.17	1.28	-0.08	0.43	765.2
	SD	194.0	141.6	234.5	33.5	53.9	0.25	0.18	0.31	0.04	0.07	
S8	Mean	5277.8	629.8	654.5	-28.5	317.5	9.88	1.18	1.23	-0.05	0.59	534.0
	SD	898.0	214.8	146.0	8.7	46.0	1.68	0.40	0.27	0.02	0.09	
S9	Mean	5225.6	411.4	894.2	-60.7	471.4	6.83	0.54	1.17	-0.08	0.62	765.2
	SD	183.8	131.1	210.7	10.2	211.1	0.24	0.41	0.28	0.01	0.28	
S10	Mean	4985.6	430.2	889.5	-37.0	399.5	6.87	0.59	1.23	-0.05	0.55	725.9
	SD	289.0	334.8	741.3	33.1	297.5	0.40	0.46	1.02	0.05	0.41	
S11	Mean	5656.9	953.9	1162.8	-79.1	288.6	8.47	1.43	1.74	-0.12	0.43	668.0
	SD	800.8	245.0	355.4	35.8	94.7	1.20	0.37	0.53	0.05	0.14	
S12	Mean	5001.0	653.3	759.2	-41.8	253.6	6.29	0.82	0.95	-0.05	0.32	795.1
	SD	428.7	349.2	540.1	23.1	193.1	0.54	0.44	0.68	0.03	0.24	
Total	V_{\max}		ML_{ts}	ML_{hs}	AP_{\min}	AP_{\max}	V_{\max}	ML_{ts}	ML_{hs}	AP_{\min}	AP_{\max}	BW (N)
Mean	5344.3		562.6	952.9	-51.9	496.3	7.98	0.82	1.39	-0.08	0.74	688.0
SD	629.5		218.0	169.0	32.4	260.3	1.32	0.32	0.25	0.05	0.41	88.9

		Bail Out Forces in Newtons (N)					Bail Out Forces in Body Weights (BW)					Body Weight
B:		V_{\max}	ML_{\min}	ML_{\max}	AP_{\min}	AP_{\max}	V_{\max}	ML_{\min}	ML_{\max}	AP_{\min}	AP_{\max}	BW (N)
S1	Mean	6228.5	-1769.0	1065.6	-525.2	1393.1	10.58	-3.01	1.81	-0.89	2.37	588.7
	SD	144.0	332.3	34.7	123.9	201.2	0.24	0.56	0.06	0.21	0.34	
S2	Mean	7893.8	-304.9	717.9	-74.3	3014.2	13.41	-0.52	1.22	-0.13	5.12	588.6
	SD	1552.4	187.8	651.9	59.7	74.0	2.64	0.32	1.11	0.10	0.13	
S3	Mean	8218.6	-839.6	350.9	-338.8	2491.7	12.48	-1.28	0.53	-0.51	3.79	658.3
	SD	1007.0	130.6	59.1	79.3	175.9	1.53	0.20	0.09	0.12	0.27	
S4	Mean	7006.6	-1501.5	743.9	-570.6	2398.2	8.75	-1.87	0.93	-0.71	2.99	810.1
	SD	763.8	96.0	25.4	87.5	210.0	0.95	0.12	0.03	0.11	0.26	
S5	Mean	11866.4	-466.0	2448.7	406.6	2638.5	16.67	-0.65	3.44	-0.57	3.71	712.2
	SD	1678.4	183.5	611.9	119.4	54.2	2.36	0.26	0.86	0.17	0.08	
S6	Mean	7428.3	-344.5	519.7	-1366.5	2236.1	11.51	-0.53	0.81	-2.12	3.47	645.3
	SD	250.4	67.8	244.4	119.5	181.7	0.39	0.11	0.38	0.19	0.28	
S7	Mean	7636.5	-632.7	977.3	-565.9	2114.6	9.98	-0.83	1.28	-0.74	2.76	765.2
	SD	417.7	117.1	91.9	90.7	96.0	0.55	0.15	0.12	0.12	0.13	
S8	Mean	9061.9	-560.1	520.0	-110.1	2866.4	16.97	-1.05	0.97	-0.21	5.37	534.0
	SD	2907.7	71.6	379.6	112.9	365.8	5.45	0.13	0.71	0.21	0.69	
S9	Mean	8446.4	-78.7	933.3	-732.6	1953.8	11.04	-0.10	1.22	-0.96	2.55	765.2
	SD	1399.6	20.0	188.1	488.1	494.2	1.83	0.03	0.25	0.64	0.65	
S10	Mean	9034.5	-921.0	1160.9	-327.4	3794.3	12.45	-1.27	1.60	-0.45	5.23	725.9
	SD	1944.7	54.4	622.1	235.7	661.2	2.68	0.07	0.86	0.32	0.91	
S11	Mean	5963.5	-416.1	1048.8	-628.6	2000.9	8.93	-0.62	1.57	-0.94	3.00	668.0

(continued)

Table 1. Continued.

		Bail Out Forces in Newtons (N)					Bail Out Forces in Body Weights (BW)					Body Weight
S12	SD	445.6	51.2	615.6	367.6	202.6	0.67	0.08	0.92	0.55	0.30	795.1
	Mean	9754.6	-841.3	1946.2	-373.5	2425.9	12.27	-1.06	2.45	-0.47	3.05	
	SD	671.3	223.9	496.9	96.2	337.2	0.84	0.28	0.62	0.12	0.42	
	Total	V_{\max}	ML_{\min}	ML_{\max}	AP_{\min}	AP_{\max}	V_{\max}	ML_{\min}	ML_{\max}	AP_{\min}	AP_{\max}	BW (N)
	Mean	8211.7	-722.9	1036.1	-501.7	2444.0	12.09	-1.07	1.49	-0.72	3.62	688.0
	SD	1614.7	49.5.0	606.3	336.4	607.7	2.63	0.76	0.80	0.51	1.07	88.9

Discussion

We found that landing on the skateboard provided significant ($P < 0.05$) shock attenuation, lessening the peak vertical impact forces experienced by the skateboarder when successfully landing a rail slide. Average vertical bail-out forces were 12.09 BW compared to 7.98 BW during the landing trials (Table 1). This result may be explained by considering the skateboard to be a sprung element in the system of skateboarder and skateboard. The board itself is usually made of laminated wood and flexes in both the vertical and medial-lateral planes of motion under heavy loads. In addition, the trucks that support the wheels incorporate bushings (shock absorbers) to provide a dampening system to the board and the polyurethane wheels themselves are compliant as well. We assume that each of these elements provides some contribution to the overall reduction in impact force, though further analysis on the effect of each of these elements is needed.

Because the skateboarders used a different pattern of movement in the L and in the BO condition we must consider that the differences we observed in the L vs. BO VGRF peaks may have been, in part, a consequence of the movement pattern and not entirely the result of the skateboard's shock attenuating properties. It seems reasonable to assume that these expert skaters would naturally adopt a more shock-absorbing pattern of landing movement to accommodate the higher forces of the BO. In our video record and by casual observation, we observed just that – a pattern of movement that is intended to attenuate peak forces and distribute the impact loads during a BO. On the other hand, landing on the board successfully also requires certain precisely controlled, stiffer, leg movements that are inconsistent with enhanced shock attenuation by the musculoskeletal system. In general, we observed that differences in the pattern of movements that characterize the L vs. BO would tend to increase peak VGRFs in the L and decrease peak VGRFs in the BO. This tendency makes it less likely

that we would find a significant difference between the two conditions (L vs. BO) and more likely that the skateboard's influence is in fact being muted by the movements of the skaters. Although it is important to acknowledge that the patterns of skater movement influence peak VGRF's in both landing outcomes, we think these data along with the observed tendencies in the pattern of movements, support the conclusion that the skateboard makes a major shock attenuating contribution.

The main implication of this finding is that skateboard manufacturers can use these force data to help them design decks, bushings, and trucks that are tuned to the characteristic force curves we observed in order to enhance the skateboard's shock attenuation capacity.

Another factor that can influence shear and vertical forces and may be responsible for some of the variability we observed is approach speed, i.e. the horizontal speed of the skater and skateboard as they leave the ground when leaping onto the rail. Prior to leaping onto the rail the subjects rolled down a short sloped ramp to gain some speed and along a flat runway 4.88 m in length. At the end of this runway the subjects would reach a horizontal speed of approximately 4.5 m/s as they began the ollie maneuver that would carry them up onto the rail. Although we observed that the differences in this approach speed from trial to trial as well as between subjects appeared to be small, it is nonetheless a source of variability for the force data we observed. However, we could not control approach speed as it was a critical component of the individual subject's technique. We view this as contributing factor, along with other elements of individual technique, in the variability that the individual skate style brings to the data.

Shear forces in the landing trials were found to be quite variable both within subjects and between subjects. This seemed largely due to two factors: the instability of the skaters on their boards shortly after landing and slight differences in orientation of the

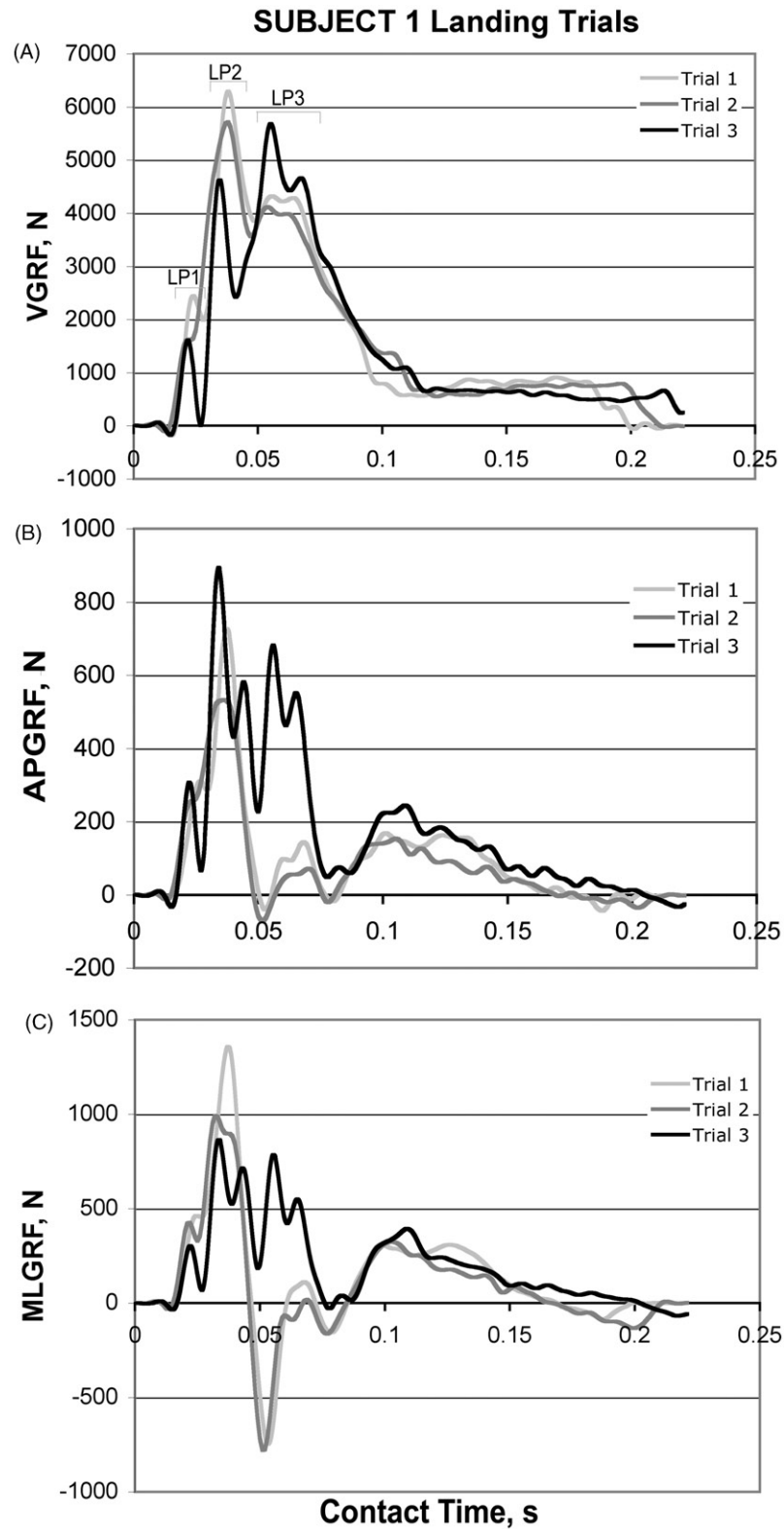


Figure 2. (A) Three trials of vertical ground reaction force (GRF) data for one subject performing the Landing (L) maneuver. (B) Three trials of anterior–posterior plane GRF data for Subject 1 performing L maneuver. (C) Three trials of medial–lateral plane GRF data for one regular footed subject performing the L maneuver. Units are in Newtons and contact time in seconds.

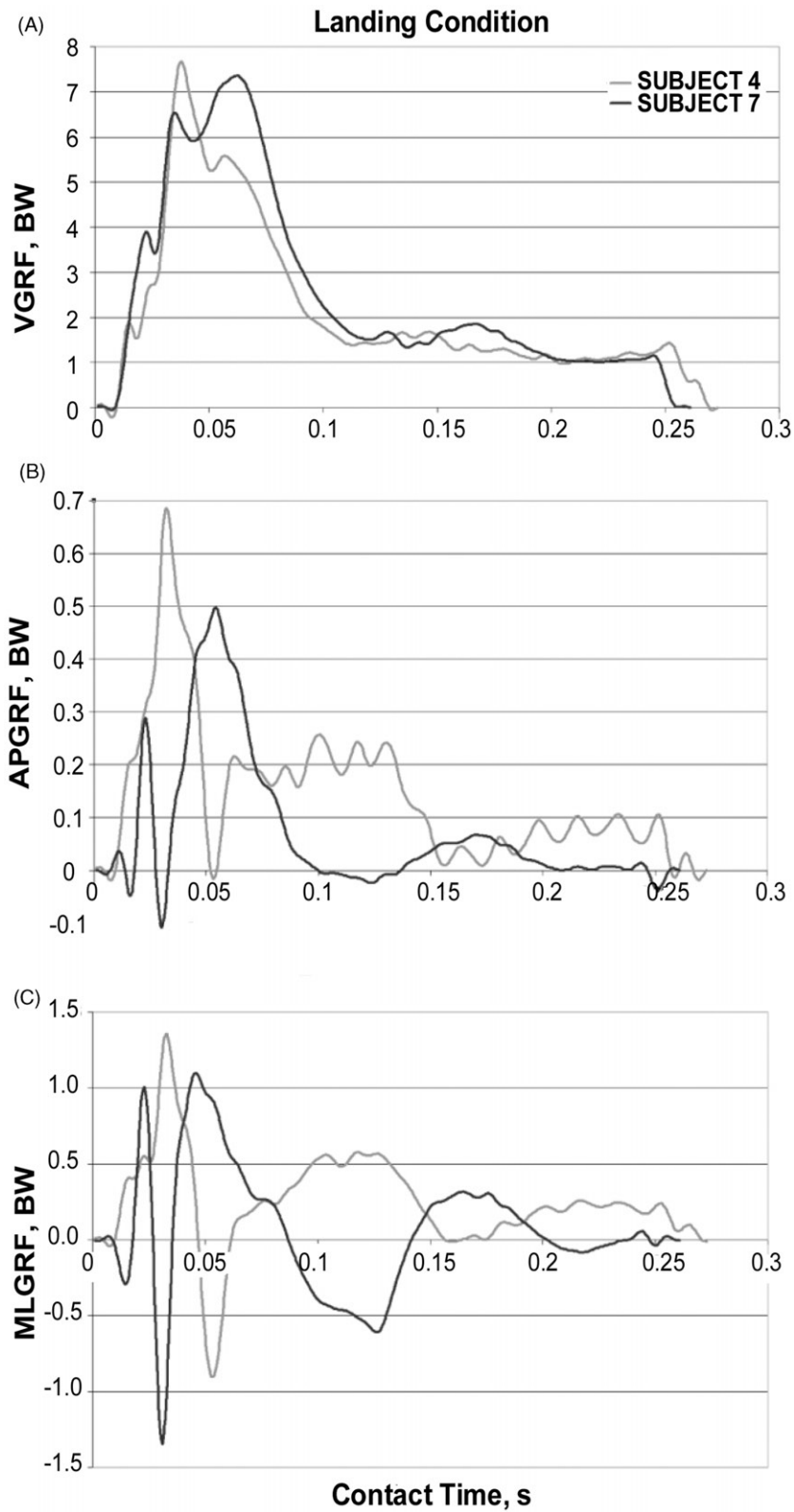


Figure 3. Average ground reaction force (GRF) data for two subjects with different riding styles and landings performing the Landing (L) maneuver. Units are expressed in body weights (BW) and contact time is in seconds. Each individual subject's curve represents the average of his three trials. (A) Vertical GRF data. (B) Anterior–posterior GRF data. (C) Medial–lateral GRF data. Subject 4 rode regular footed while Subject 7 rode goofy footed.

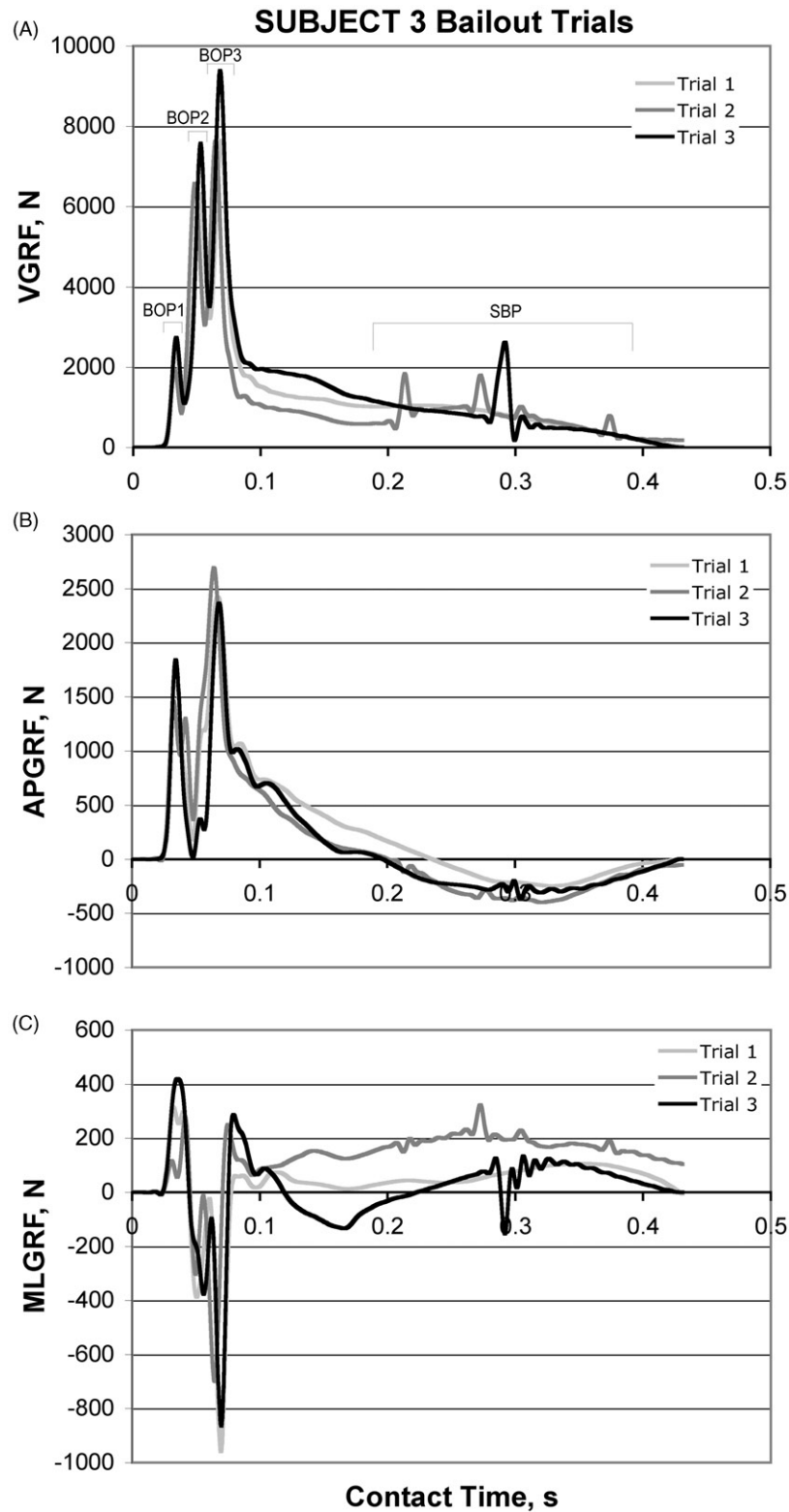


Figure 4. (A) Three trials of vertical ground reaction force (GRF) data for one subject performing a bail-out (BO) maneuver. (B) Three trials of anterior–posterior plane GRF data Subject 3 performing BO maneuver. (C) Three trials of medial–lateral plane GRF data for one subject performing the BO maneuver. Units are in Newtons and contact time in seconds. In some trials subsequent peaks (SBP) occurring 200–400 ms after initial impact also occurred and were caused by the skateboard coming down and striking the force plate while the subject was still on the plate.

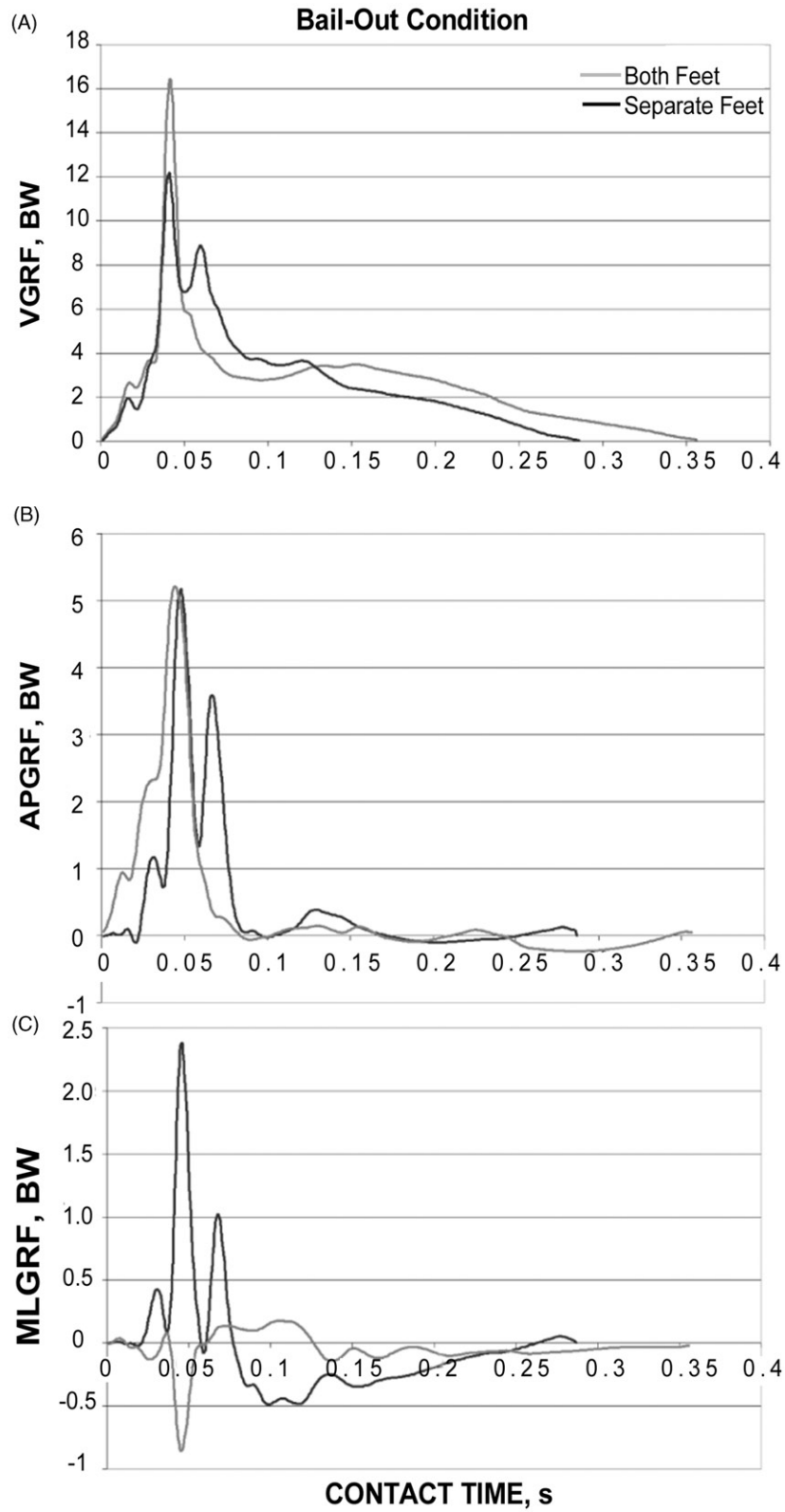


Figure 5. Representative ground reaction force (GRF) data of both simultaneous feet and separate feet bail-out (BO) landings. Units are expressed in body weights (BW) and contact time is in seconds. (A) Vertical GRF data. (B) Anterior–posterior GRF data. (C) Medial–lateral GRF data.

board upon landing. On first landing, the subject may not have been centered on the board in the shear planes. The instability of these landings, both medial to lateral and fore to aft, required the subject to make corrective movements to stabilize their position on the board. These stabilizing movements, which were different for each subject and each landing created, in part, the observed variability in the shear forces that are visible in Figures 2 and 3. The orientation of the board coming down and landing on the force plate in the shear planes was also unique for each landing. This may explain in part the higher than expected braking forces found during the landing trials in this study. Landing orientation of the board was not monitored in this study.

When a bail-out was required and subjects landed on their feet, significantly higher forces were experienced. The magnitudes of the impact forces in skateboarding are among the highest reported for sports and other activities (Nigg 1985, Ramey and Williams 1985, McNitt-Gray 1993, Kwok *et al.* 2003). This may in part support the clinical observations of a relatively high incidence of acute injuries among the skateboarding population. McNitt-Gray (1993) studied bare-foot gymnastics landing dismounts from three heights (0.32, 0.72 and 1.28 m) and found vertical ground reaction forces ranging from 3.9 to 11 times BW. Given the fact that our subjects consistently jumped off the handrail at similar heights ranging from 0.90 to 1.28 m and with shoes on, we would have expected to observe similar if not lower VGRF impacts forces in our study. However, the results we found showed impact forces consistently in the 9–17 BW range (Table 1).

One reason for this difference is the fact that the initial vertical velocity of our subjects sliding down the handrail was not zero in both the L and BO conditions. Unlike usual drop landings or jumps where there is no initial vertical velocity, the subjects in our study started with a significant initial vertical velocity as they left the rail which added to the effect of gravity. Differences in this initial vertical velocity, which were not monitored in this study, might also have contributed to the high variation in peak GRF's that we observed within each subject.

Army paratrooper studies have also shown similar large magnitude VGRF impact peaks. Kwok *et al.* (2003) studied simulated Army parachute landings at heights of 0.91 and 1.37 m and found mean impact VGRF peaks to be 8.9 BW (SD 2.5) and 12.7 BW (SD 5.4) at each respective height. Interestingly, the subjects in their study considered three or four jumps as a hard work day (Kwok *et al.* 2003). In comparison, skateboarders in our study reported they may have to

perform 20–30 bail-outs a day as they try to learn and master new movements on the handrails.

The shear GRF results for the BO condition were also found to be quite variable both within and between subjects. This is largely due to differences in the spatial positioning of the skateboarder's feet from trial to trial as they landed on the force plate. Some skaters landed sideways or backwards to the plane of their original direction of motion. Anterior–posterior GRF data were found to be surprisingly high, particularly the amount of aft or braking forces involved with these impact falls. Mean braking forces for the BO condition averaged 3.62 BW and ranged from 2.4 to 5.4 BW (Table 1). This is almost one and a half to two times greater than what is commonly seen in basketball lay-up landings (McClay *et al.* 1994). Corresponding high-speed video revealed skater's feet smashing into the toe box of their shoes during bail-out landings.

It is important to note that the subjects in our study were highly skilled as evidenced by their professional or top-amateur standings in competitive skateboarding. Also, in terms of body mass they were not typical of other skateboarders. In a recent survey of 797 North American skateboarders conducted by our research group, we found that the average skateboarder was younger (mean 15 years 8 months) and lower in body mass (mean 56.7 kg) than the experienced and more mature skaters used in this study. Therefore we need to exercise caution in applying these findings to the general population of skateboarders. Even though our data are scaled to body mass, making it applicable to discussions of a broader range of skater body masses, developmental and mass distribution issues may come into play, as well as factors related to skill and experience.

It is unclear how the results found in this study relate to previous epidemiological studies, which typically only report traumatic acute injuries (i.e. sprains and fractures) and the numbers of injuries incurred by skateboarders. How or why these injuries occurred is left to speculation. In the survey conducted by our research group, we also found that many skateboarders either self treat or receive parental treatment for their injuries and thus no injury history records are kept. Some of these types of injuries include severe heel and forefoot bruising as well as toe nail blackening. These overuse type injuries may be more closely linked to the extreme ground reaction forces presented in this study. It would help elucidate the actual mechanisms of injury if future epidemiological studies would simply report what injured skateboarders were doing at the time their injuries occurred. If this information were known then biomechanical data such as that presented

herein could be used to develop testable hypotheses about the etiology of various injuries.

Other board sports have reported similar unique foot and ankle injuries to their participants. In snowboarding, Kirkpatrick *et al.* (1998) reported an unusually high incidence rate of fractures to the lateral process of the talus (LPT) also known as “snowboarder’s ankle”. Although several mechanisms have been proposed, the general consensus is LPT fractures occur when the ankle receives a large axial load while it is in a dorsiflexed, externally rotated, and either inverted or everted position (Boon *et al.* 2001, Funk *et al.* 2003, Schoen 2005, Valderrabano *et al.* 2005). With similar if not greater loads and ankle movements occurring during bailouts, it is not inconceivable that skateboarders could be subject to LPT fractures as well.

Conclusion

When skateboarders land on their boards at the end of a handrail slide the impact forces they experience are significantly lower than when they bail out and land on their feet. The sprung elements of the skateboard apparently provide significant shock attenuation when landing. When skaters are unable to land on their boards (BO condition) the impact forces are quite high even in comparison with other high impact activities such as parachute landings and gymnastics. Given the musculoskeletal immaturity of typical skateboarders, footwear manufacturers and clinicians should be aware of the relatively large impact forces associated with such maneuvers. Skate shoe manufacturers should develop special technologies that reduce peak pressures and high impact and shear forces in the heel, forefoot, and toe box regions. These findings also should form the basis for future studies that would help science better understand the pathological mechanisms causing injuries in skateboarding, as well as the acute and chronic effects of exposing the lower extremity to such high forces on a regular and frequently repetitive basis.

References

- Ardent, Y.D. and Kerschbaumer, F., 2003. Injury and overuse pattern in professional ballet dancers. *Zeitschrift für Orthopädie und ihre Grenzgebiete*, 141, 349–346.
- Boon, A.J., *et al.*, 2001. Snowboarder’s talus fracture: mechanism of injury. *American Journal of Sports Medicine*, 29, 333–338.
- Frederick, E.C., *et al.*, 2006. Biomechanics of skateboarding: kinetics of the ollie. *Journal of Applied Biomechanics*, 22, 33–40.
- Funk, J.R., Srinivasan, S.C., and Crandall, J.R., 2003. Snowboarder’s talus fractures experimentally produced by eversion and dorsiflexion. *American Journal of Sports Medicine*, 31, 921–928.
- Jacobs, R.A. and Keller, E.L., 1977. Skateboard accidents. *Pediatrics*, 59, 939–942.
- Kirialanis, P., *et al.*, 2003. Occurrence of acute lower limb injuries in artistic gymnasts in relation to event and exercise phase. *British Journal of Sports Medicine*, 37, 137–139.
- Kirkpatrick, D.P., *et al.*, 1998. The snowboarder’s foot and ankle. *American Journal of Sports Medicine*, 26, 271–277.
- Kyle, S.B., *et al.*, 2002. Skateboard-associated injuries: participation-based estimates and injury characteristics. *Journal of Trauma-Injury Infection and Critical Care*, 53, 686–690.
- Kwok, P., *et al.*, 2003. A biomechanical study on the parachute landing fall. In *Proceedings of the 17th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*, Monterey, CA, 2149–2152.
- McClay, I.S., *et al.*, 1994. A profile of ground reaction forces in professional basketball players. *Journal of Applied Biomechanics*, 10, 222–236.
- McNitt-Gray, J.L., 1993. Kinetics of the lower extremity joints during drop landing from three heights. *Journal of Biomechanics*, 25, 1037–1046.
- Nigg, B.M., 1985. Loads in selected sports activities—an overview. In: D.A. Winter, *et al.*, eds. *Biomechanics IX-B*. Champaign, IL: Human Kinetics Publishers, 91–96.
- Osberg, J.S., *et al.*, 1998. Skateboarding: more dangerous than roller skating or in-line skating. *Archives of Pediatric and Adolescent Medicine*, 152, 985–991.
- Ramey, M.R. and Williams, K.R., 1985. Ground reaction forces in the triple jump. *Journal of Applied Biomechanics*, 1, 233–239.
- Schoen, D.C., 2005. The mystery of ankle problems. *Orthopaedic Nursing*, 24, 166–169.
- SGMA. 2007. *SGMA 2007 Sports & Fitness Participation Report from the USA Sports Participation Study, 1–5*. North Palm Beach, FL: SGMA International.
- Shuman, S.H., 1967. Skateboard injuries in a campus community. *Clinical Pediatrics*, 6, 252.
- Stacoff, A., Kaelin, X., and Stuessi, E., 1998. Impact in landing after a volleyball block. In: G. De Groot, A.P. Hollander, P.A. Huijting and G. van Ingen Schenau, eds. *Biomechanics XI-B*. Amsterdam: Free University Press, 694–700.
- Valderrabano, V., *et al.*, 2005. Snowboarder’s talus fracture: treatment outcome of 20 cases after 3.5 years. *American Journal of Sports Medicine*, 33, 871–880.
- Valiant, G.A. and Cavanagh, P.R., 1985. A study of landing from a jump: implications for the design of a basketball shoe. In: D.A. Winter, R.W. Norman, R.P. Wells, K.C. Hayes and A.E. Patla, eds. *Biomechanics IX-B*. Champaign, IL: Human Kinetics, 117–122.