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SANDS, WA, KELLY, B, BOGDANIS, G, BARKER, L, DONTI, O, MCNEAL, JR and PENITENTE, Gabriella

Published version

SANDS, WA, KELLY, B, BOGDANIS, G, BARKER, L, DONTI, O, MCNEAL, JR and PENITENTE, Gabriella (2019). Comparison of bungee-aided and free-bouncing accelerations on trampoline. Science of Gymnastics Journal, 11 (3), 279-288.

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Primary Author:
William A Sands, Ph.D., FACSM
U.S. Ski and Snowboard Association
2300 S 2100 E
Salt Lake City, UT 84109
385.887.1243
wmasands@hotmail.com

Bret Kelly, MS
U.S. Ski and Snowboard Association
1 Victory Lane
Park City, UT 84060
435.714.2031
bkelly@ussa.org

Gregory C. Bogdanis, Ph.D.
School of Physical Education and Sport Science
National and Kapodistrian University of Athens
41 Ethn. Antistasis Str. Dafni
172 37, Athens, Greece
+30210-7276115
gbogdanis@phed.uoa.gr

Leland Barker, Ph.D.
Creighton University
Department of Exercise Science and Pre-Health Professions
2500 California Plaza
Omaha, NE 68178
402.280.2700
Leland.Barker@cirquedusoleil.com

Olyvia Donti, Ph.D.
Sports Performance Laboratory
School of Physical Education & Sport Science,
National and Kapodistrian University of Athens
172 37 Athens, Greece.
odonti@phed.uoa.gr

Jeni R McNeal, Ph.D. CSCS*D
Dept PEHR, 200 Phys Ed. Bldg
Eastern Washington University
Cheney, WA 99004, USA
509.359.2872
jeni_mcneal@hotmail.com

Gabriella Penitente, Ph.D.
Senior Lecturer in Sport and Exercise Biomechanics
Sheffield Hallam University
Collegiate Crescent
Sheffield, S10 2BP, UK
+44 (0)114 225 2304
g.penitente@shu.ac.uk

Comparison of Bungee-aided and Free-bouncing Accelerations on Trampoline

Trampolines remain the single best apparatus for the training of aerial acrobatics skills. Trampoline use has led to catastrophic injuries from poor landings. Passive injury prevention countermeasures such as specialized matting have been largely ineffective. Active injury countermeasures such as hand spotting, "throw-in" mats, and overhead spotting rigs provide the most effective methods. The recent addition of several bungee cords between the ropes and the gymnast's spotting harness has resulted in altered teaching and coaching of trampoline-related acrobatics. Bungee cords have eliminated the need for a coach/spotter to manage the ropes during skill learning. The purpose of this study was to assess the influence of the addition of bungee cords with a traditional rope-based overhead spotting rig. There is a paucity of any research involving trampoline injury countermeasures. Ten experienced trampoline acrobatic athletes (5 males, 5 females) from the U.S. Ski and Snowboard Association Aerials National Team performed 10 bounces as high as they could control. A triaxial accelerometer (200 Hz) characterized 10 bungee cord aided bounces and 10 free-bounces on a trampoline from each athlete. Bed contact times, peak accelerations, and average accelerations were obtained. The results supported our hypotheses that the bungee-aided bounces achieved only 40% (average) to 70% (peak) of the free-bouncing accelerations (all $\rho < 0.001$ ***and all*** $\eta^2_{partial} > 0.092$***). The bed contact time was approximately 65% longer during the bungee-aided bounces (***$\rho < 0.001$***). Bungee cords may reduce the harshness of landings on trampoline.***

Comparison of Bungee-aided and Free-bouncing Accelerations on Trampoline

Introduction

Trampolines have received increased attention as both a performance apparatus and as a training tool for acrobatic athletes. Trampolines offer athletes the ability to rise as high as five or more meters in the air with minimal physical effort (Eager, Chapman, & Bondoc, 2012), practice difficult skills, and land on a flexible and elastic trampoline bed. However, trampolines can embody a revenge effect (Tenner, 1996). Providing easy access to high jumps that gives more air time to learn a skill also results in increased velocity and force at landing. Revenge effects are unanticipated consequences of some change to a complex system (Tenner, 1996). An uncontrolled fall that often occurs during learning may increase the risk of a serious injury aggravated by a greater descent distance.

The dangers of trampolines have been well documented for decades (Council on Sports Medicine & Fitness, 2012; Kakel, 2012; Torg, 1987). The apparatus was banned from schools for years following position statements from the American Association of Health, Physical Education, Recreation, and Dance (J.O.P.E.R., 1978), American Academy of Pediatrics (American Academy of Pediatrics, 1982, 1999), and the American Academy of Orthopedic Surgeons (American Academy of Orthpaedic Surgeons, 2001).

However, trampoline is a competitive sport with more than a million of active athletes worldwide and an Olympic discipline since 2000 (Jensen, Scott, Krustrup, & Mohr, 2013). Despite the amount of research associated with trampoline jumping, evidence is limited on injury prevention countermeasures for trampoline include both passive and active methods (Sands, 2000). Passive methods involve the use of various types of padding. Specialty mats can be used to cover the trampoline frame as well as the springs of the trampoline bed. Mat tables are placed flush with the height of above-ground trampolines, which are then padded with thick mats. Floor matting is also common. Unfortunately, trampoline injury research has indicated that none of the passive countermeasures are capable of preventing injury (American Society for Testing and Materials, 1990; Torg & Das, 1984). Active injury prevention countermeasures include, “throw-in” mats (Sands & Drew, 2007), and various types of manual hand and belt spotting (USA Tumbling and Trampoline, 2007). Throw-in mats are mats that are pushed onto the trampoline bed by coaches or athletes adjacent to the trampoline when an athlete is out of control. Throw-in mats may also be used to simply reduce the energy of the bounce (Sands & Drew, 2007).

Perhaps the most effective injury countermeasure for trampolines is the overhead spotting belt or rig. The overhead spotting belt involves a snug waist and hip harness which is attached to ropes or bungee cords which are attached to the ceiling or a rigid frame (Figure 1). Such overhead spotting rigs allow the athlete to be suspended from above so that they are supported throughout the bounce, and have protection in the event of an unexpected fall. Overhead spotting rigs provide the highest degree of safety for athletes performing on a trampoline (Figure 1). For example, USA Diving, in their U.S. Diving Safety Certification manual, requires that all divers using a trampoline as a training tool, must use an overhead spotting rig or hand spotting with a belt and short ropes, and the coach must have completed special training provided by U.S, Diving (Kimball, 1999b).

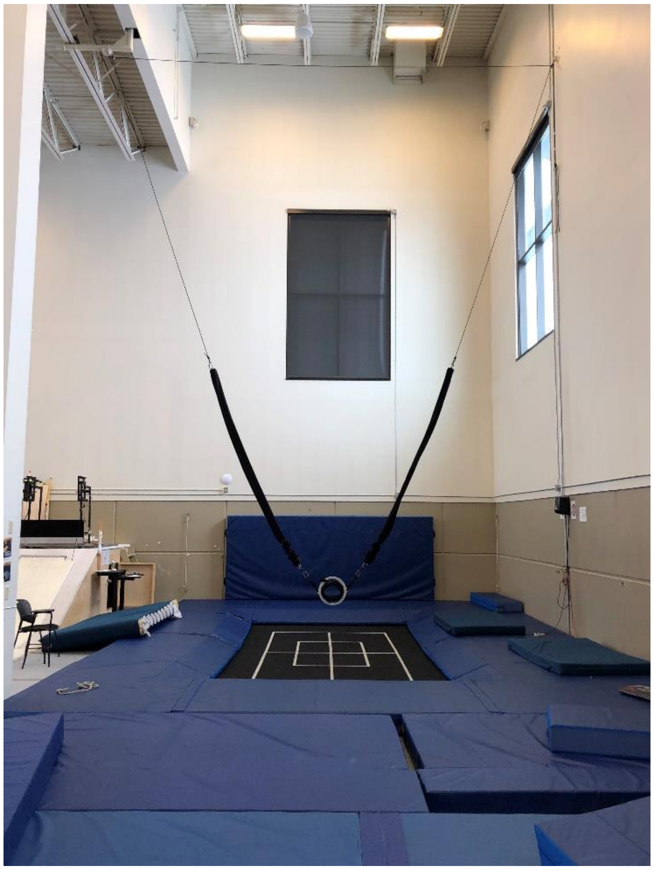

Figure 1. Overhead spotting rig using ropes and bungee cords.

Overhead spotting rigs have been ubiquitous for decades (Figure 1). However, the addition of bungee cords has been more recent. There are two primary ways to support the athlete from an overhead spotting rig: using ropes or by bungee cords. In a rope-based overhead rig, two ropes are suspended from the ceiling or a rigid frame directly above the center of the trampoline (Figure 1). The ropes pass through pulleys spaced widely apart, with one end of each rope attaching to the sides of a harness worn around the athlete's waist. The other ends of the ropes are controlled through active muscular effort provided by a skilled spotter (typically a coach). As the athlete bounces the spotter has to maintain tension on the ropes in order to provide continuous support for the athlete by avoiding slack in the ropes. The spotter accomplishes this by pulling down on the ropes as the athlete bounces upward, and letting the ropes rise upward as the athlete descends downward in the bounce. This up-and-down motion of the grip of the spotter on the rope requires considerable skill to maintain proper tension and timing (Hennessey, 1990;

Kimball, 2007; Sands, 1990, 2000). If the athlete experiences an error or an unexpected fall, the spotter holds the ropes tightly and slows the athlete's descent. The spotter needs to be strong, heavier than the athlete, and possesses quick reflexes with high vigilance. Often the spotter is pulled completely off the floor while lowering the athlete.

An overhead spotting rig which utilizes bungee cords to attach to the athlete removes the need for a skilled human spotter. The ropes and bungee cords need only be set in their optimal tension position and mechanically fixed (Figure 1). Setting the tension of the ropes and bungee cords is usually accomplished by an electric winch that pulls the ropes while stretching the bungee cords (Figure 1). The tension applied by the bungees and ropes lifts the athlete off of the trampoline bed. To begin bouncing, a teammate or assistant has to pull downward on the athlete in order to stretch the elastic bungees and initiate contact with the trampoline bed. After several preparatory bounces, the athlete is able to effectively use the trampoline spring characteristics and the recoil of the elastic bungee cords to rise into the air. Athletes can bounce higher with the combined forces from the trampoline springs and the bungee cords. Most importantly, high bounces are paired with rapid deceleration of the athlete as he or she returns back to the trampoline bed, softening the landing. The assured soft landing frees the athlete to perform many repetitions of difficult skills without a threat of falling harshly and possibly experiencing injury.

Despite the widespread use of bungee cord overhead spotting rigs in trampoline, no studies have been conducted which quantifies how this system affects the bouncing athlete. The purpose of this study was to characterize the differences between bungee cord aided bouncing and bouncing without the aid of a bungee apparatus, known as 'free-bouncing'. As the first study of bungee cord aided trampoline bouncing the results may provide information that can be used to determine the levels of accelerations involved. We hypothesized that bouncing with the aid of bungees and bouncing freely would show **s**tatistically different bounce characteristics with the bungee-aided bounces showing longer acceleration times and lower peak and average accelerations.

Methods

Participants. Five male (Mean ± SD; age 23.02 y ± 2.45 y; height 168.66 cm ± 9.77 cm; mass 73.2kg ± 8.22 kg) and five female (Mean ± SD; age 20.97 y, 3.43 y; height 162.52 cm, 6.17 cm; mass 59.56 kg, 5.07 kg) experienced trampoline athletes from the U.S. National Aerials Team and the Center of Excellence of the U.S. Ski and Snowboard Association volunteered to participate in this study.

Figure 2. Image of the ends of bungee cords, the plugs inside the bungee cords that hold the ends of the bungees in place, and the plastic circle with holes arranging and holding the bungee ends.

Equipment. Athletes bounced on a large trampoline called a Super-Tramp (bed size 3.05m x 6.10m, one-string bed, Rebound Products, Thornhill, Ontario, Canada). The bungee setup included five tubular cords (3.66m long relaxed and 1.27cm diameter) attached at each end to holes in a plastic circle with end plugs that prevented the cords from slipping out of the attachment device (Figure 2). The bungees descended from ropes that were in turn attached to steel cables. Steel cables ran from the ropes to two pulleys and then were joined to an electric winch that raised and lowered the tension on the athlete, belt harness, bungees, and ropes.

Instrumentation. Accelerations were obtained from a PASCO Scientific, triaxial accelerometer (PASCO Scientific, Roseville, CA, USA PS-3202, ± 16 G all axes, no electronic filtering) attached rigidly to a waist belt that was worn tightly about the waist of the athlete placing the accelerometer posterior to the lumbar spine at approximately the level of lumbar vertebrae L3 to L4 (Simons & Bradshaw, 2016). Acceleration data were transmitted via Blue Tooth™ to a laptop computer. Data were captured (200 Hz), displayed, and stored using Capstone software (PASCO Scientific, Roseville, CA, USA, V1.11.1). Calibration was performed using gravitational vertical. Calibration was conducted by rotating the accelerometer systematically such that one of the three axes of the accelerometers was oriented to the line of gravity approximately 9.806 m/s^2, while the remaining axes measured approximately 0 m/s^2.

Procedures. At arrival for testing the athletes were weighed, measured for height, and queried for birthdate. The athletes were fitted with the belt and accelerometer. Athletes performed a self-selected number of initial bounces, and progressively increased bounce height until they verbally announced that they were bouncing at their greatest controllable height. The athletes first completed the bungee-aided trials, followed by free bouncing (belt and bungees removed). The fixed order of conditions was required because of the athletes' training schedules. The highest ten sequential bounces were used as the bounce trials to characterize each condition's acceleration profile, although sampling was undertaken throughout all bounces, similar to previous procedures (Briggs, 2014; Harden & Earnest, 2015). The interval between the two bounce conditions was approximately five minutes.

Data analysis. Descriptive statistics and athlete demographics were collected and recorded. Following data capture and storage, MatLab™ (Natick, MA, USA) was used for data extraction and analysis. Initially, 9.806 m/s/s was added to the vertical-axis signal so at rest the accelerometer read 0 m/s/s. The z-axis was -9.806 m/s/s when the accelerometer was at rest on a flat surface. The added value for gravity was due to the orientation of the accelerometer on the belt of the athlete. Resultant acceleration was calculated from triaxial accelerations (resultant acceleration = $\sqrt{(x^2 + y^2 + z^2)}$). Using the resultant is necessary to account for the orientation of the accelerometer, which is subject to change during human movement. The vertical acceleration adjustment converts free fall *resultant* acceleration to 0 m/s/s, which is critical to defining the start and end points of acceleration due to the trampoline or bungee systems.

Acceleration time, peak acceleration, and average acceleration were obtained from the acceleration data and MatLab™ algorithms. Acceleration time during the bungee trials represents the entire acceleration performed by the bungee and trampoline (acceleration occurs pre- and post-trampoline contact), while acceleration time during the free trials represents acceleration performed by the trampoline alone. Bounce acceleration time, peak acceleration, and average acceleration were obtained from the acceleration data and MatLab™ algorithms. The acceleration data were digitally filtered using a 4th-order low-pass Butterworth filter with a cutoff frequency of 50Hz. The filtering was used on all axes individually prior to calculating the resultant acceleration. A bounce was defined as the time from acceleration rising above zero to acceleration reaching zero again.

Trends across the ten trials (i.e., bounces) were analyzed using procedures provided by Hopkins (http://www.sportsci.org/resource/stats/relycalc.html#bot). The Hopkins procedure calculates correlations and intraclass correlation coefficients (ICC) for pairs of trials such as, trial 1 with trial 2, trial 3 with trial 4, and so forth. The final ICC for the ten trials is determined by the mean of the paired ICCs.

All data were analyzed using IBM SPSS software (IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp). The ten trials were collapsed to means for each athlete, condition, and variable resulting in ten means of trials for three variables, and two conditions. Three one-way repeated measures ANOVAs (RMANOVA) were calculated to assess differences (i.e., bungee-aided vs free-bounce) for the variables: acceleration time, peak acceleration, and average acceleration. Effect size estimates were calculated as partial eta^2 ($\eta^2_{Partial}$), values: ≤ 0.02 = small, 0.02 to 0.13 = medium, 0.13 to 0.26 = large (Cohen, 1988). Experiment-wise statistical significance was set at $\rho \leq 0.05$. Type I error correction for the three RMANOVA procedures was provided by the Dunn-Sidak method (Sokal & James Rohlf, 1969).

Results

The means of the ten trials from the two conditions and three variables were examined first for differences by sex. No statistical differences between the sexes were observed (all $\rho > 0.05$). Since the means of the ten trials did not differ statistically by sex, the data were collapsed across sex (all $\rho > 0.05$). The Shapiro-Wilks test for normality revealed that all variables met normality assumptions (all $\rho > 0.05$). Four of the six variables showed excellent ICCs (all > 0.90) (Table 1).

The negative and low ICC values for the free-bounce acceleration times and for free-bounce average accelerations indicated a near complete lack of pairwise stability of the trials of the ten bounces. Closer inspection of these data showed no consistent pattern of variability such as increasing values indicative of learning or decreasing values indicative of fatigue. Therefore, because four of the six variables' ICCs. were extremely high, CoVs were low or modest for all six variables (i.e., bungee-aided acceleration time, bungee- aided peak acceleration, bungee-aided average acceleration, free-bounce acceleration time, free-bounce peak acceleration, and free-bounce average acceleration), a reluctance to discard data (Henry, 1950), and no apparent pattern of variations across trials, all data were retained and means were calculated utilizing all ten trials for each athlete and bounce condition (Kroll, 1967). The poor ICCs supported observations that the athletes had more variability during free-bounces (Figure 3). Figure 4 shows all bounces for both conditions from one athlete.

Table 1.

Trials Analyses

Variables	ICC	Lower	Upper	CoV(%)	Std Dev

Bungee-Aided		CI Bound	CI Bound		
Acceleration time (s)	0.948	0.892	0.981	6.74	4.80
Peak Acceleration (m/s/s)	0.960	0.917	0.986	3.73	1.41
Average Acceleration (m/s/s)	0.970	0.937	0.989	1.99	1.87
Free-Bounce					
Acceleration time (s)	-0.099	-0.178	0.107	11.38	3.48
Peak Acceleration (m/s/s)	0.987	0.972	0.995	2.25	0.90
Average Acceleration (m/s/s)	0.271	0.059	0.589	10.30	2.46

ICC = intraclass correlation coefficient
Lower CI Bound = Confidence interval lower bound
Upper CI Bound = Confidence interval upper bound
CoV = Coefficient of variation
Std Dev = Standard deviation

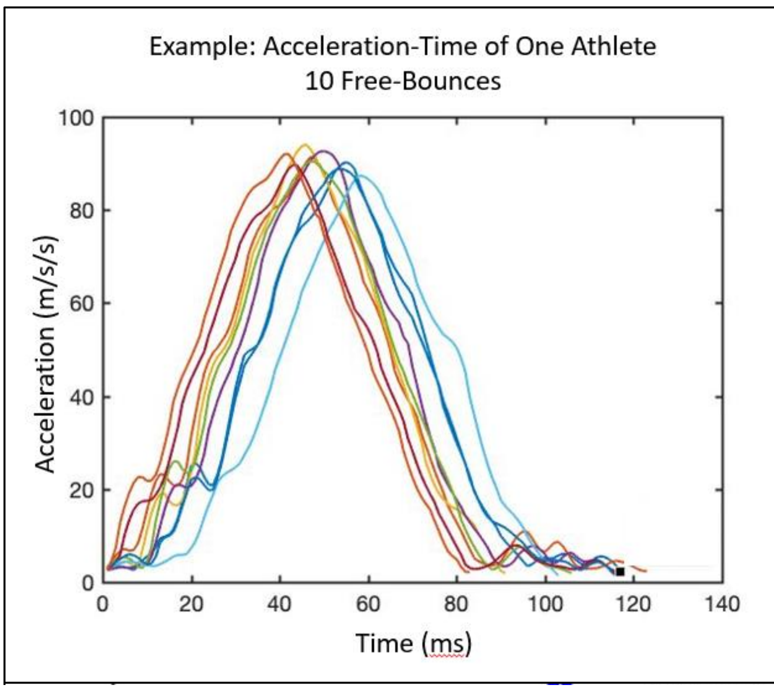

Figure 3. Example of acceleration-time data for one athlete performing in the free-bounce condition.

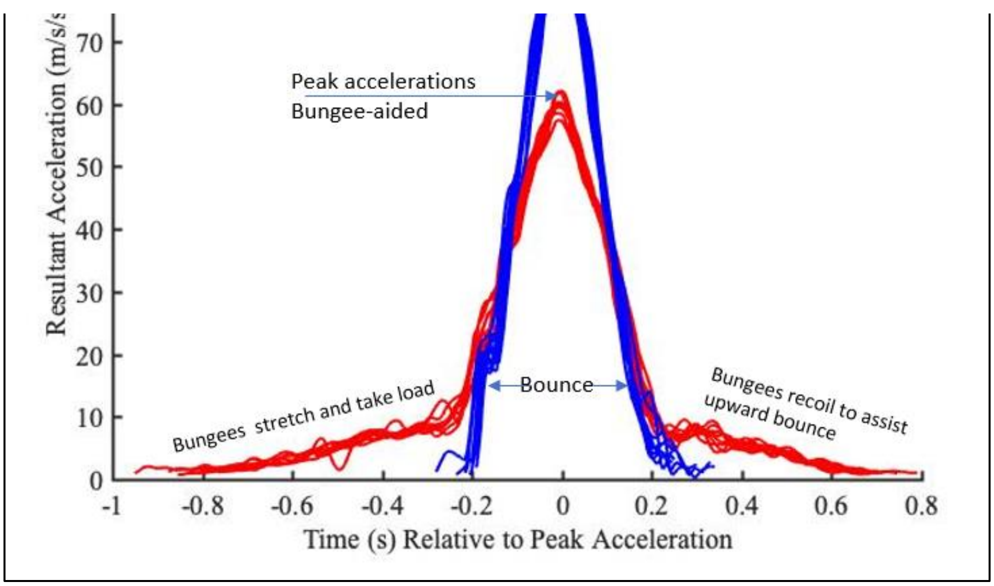

Figure 4. Comparison of Bungee-aided and Free-bounce acceleration-time data.

Descriptive information from the three variables and two conditions are shown in Table 2. The RMANOVA analyses for the three variables comparing bungee aided bounces versus free-bouncing conditions are shown in Table 3. The Sphericity assumption was met and no adjustment of degrees of freedom was merited.

Bungee acceleration times were statistically longer for the bungee-aided condition (almost 3 times longer, 290.2%). Peak accelerations for bungee-aided bounces were statistically lower (70%). Average bungee-aided accelerations were statistically lower (41.1%). Acceleration times were statistically longer for the bungee-aided condition (almost 3 times longer, 290.2%). Peak and average accelerations were statistically lower (70% and 41.1%, respectively) in the bungee-aided condition compared to free bouncing.

Table 2. *Descriptive Data – Bounce Variables*

Variables	Mean	Standard Error	95% CI Lower Bound	95% CI Upper Bound
Bungee-Aided				
Acceleration time (s)	1.486	0.091	1.280	1.692
Peak Acceleration (g)	6.945	0.302	6.261	7.629
Ave Acceleration (g)	1.720	0.081	1.536	1.905

Free-Bounce				
Acceleration time (s)	0.512	0.010	0.491	0.534
Peak Acceleration (g)	9.913	0.381	9.051	10.775
Ave Acceleration (g)	4.185	0.110	3.937	4.423

Table 3. *Results of ANOVAs comparing bungee-aided bounces with free-bouncing.*

Tests	$F_{(1,9)}$	Sig.	$\eta^2_{Partial}$	Power
Bungee-Aided vs Free Bounce				
Acceleration time (s)	108.01	<.001	0.923	1.0
Peak Acceleration (m/s/s)	207.04	<.001	0.958	1.0
Ave Acceleration (m/s/s)	342.90	<.001	0.974	1.0

Discussion

Our original hypothesis was supported in that the two conditions differed with longer acceleration times and lower peak and average accelerations in the bungee-aided condition. Moreover, the effect size statistics indicate that the differences were very large (i.e., all $\eta^2_{partial} > 0.75$). The problem with bounce data stability was troubling and a limitation of this study with regard to the athlete's abilities to bounce under control. This problem is supported by the larger CoVs of the bungee-aided bounces acceleration times and average accelerations. In spite of the poor ICCs from acceleration time and average accelerations, we believe that the acceleration times and average accelerations do not represent error but rather the actual variability of the individual athletes' performance values.

The decreased peak and average accelerations found with the bungee-aided bounces helps clarify how much the bungee cords reduce the harshness of landings from 41% to 70% as compared to free-bouncing. Given this, it is important for coaches and practitioners to utilize bungee-aided conditions, especially during the execution of complex and new or technical skills. In addition, since all the jumps perfo9rmed on a trampoline are maximal or near maximal, the metabolic load and neuromuscular fatigue are also high (Jensen et al., 2013).

The accelerations experienced by both types of bounce conditions studied here are greater than those used by roller coaster designers (+4-6g) (Elvin, 1999; Smith & Meaney, 2004). Spine injuries have been studied from the Rattler roller coaster in San Antonio, TX, for a 19-month period in 1992 and 1993 (Freeman, Croft, Nicodemus, Centeno, & Elkins, 2005). The results of the roller coaster study of 656 reported spine injuries showed that relatively low vertical peak acceleration levels (+4-6g) and horizontal acceleration g levels of 1.5g sustained occurred in less than 100ms (Smith & Meaney, 2004). Although reports of the maximum acceleration to the head are important, information is incomplete without the duration of the force and direction. The durations of the applied accelerations in the referenced study were at least five times briefer than those observed in the present study, and all of the acceleration directions in the present study were positive (i.e., vertical). Estimated maximum acceleration values obtained from injurious bungee jumping have reached 7-8g (Hite, Greene, Levy, & Jackimczyk, 1992). By g value alone, the National Aeronautics and Space Administration has indicated that sustained g levels of this magnitude may easily injure an astronaut's neck or spine (Hite et al., 1992). Bungee jumping is not the same as the task assessed in this study while some factors are shared.

Although the bungee-aided method of bouncing safety is helpful, this method may not be a panacea. Diving coaches have demonstrated that a skillful coach/spotter can aid or detract from somersaulting angular velocity by “bumping” the athlete through small and quick tugs on the spotting ropes mid-somersault (Kimball, 1999a, 2007). Moreover, the use of bungee-aided bounces and the accompanying ropes precludes the practice of extreme skiing and parkour skills such as “corks,” “grabs,” and modified somersaults with combinations of body shapes because the skis or legs strike the bungees.

Conclusion

The etiology of trampoline injuries is well documented in the literature (Esposito, 2003; Nysted & Drogset, 2006; Silver, Silver, & Godfrey, 1986), and an alarming magnitude of serious injuries (e.g. cervical spine) have been reported. Bungee-aided jumping is commonly practiced as an effective means to prevent injury from an uncontrolled fall and to provide optimal conditions to learn difficult skills and correct technical errors. This study presents the first data that describes the behavior of bungee-aided bouncing on a trampoline. With no comparative data found in the literature, one is forced to compare with tangentially related studies. While not ideal, related literature from different tasks can present some interesting, but in the end, poor comparisons. In practical terms, bungee cord spotting devices, such as the one described here, can reduce peak and average accelerations substantially. Acceleration reduction favors the safety and comfort of the athlete bouncing on trampoline. Lower accelerations translate to an increased number of repetitions prior to fatigue, an increased number of repetitions that allow more learning repetitions due to the freedom to learn by trial and error, less chance of a harsh impact and injury, and freeing the former spotter to shift from spotting to coaching.

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