COMPARISON OF FLOOR EXERCISE APPARATUS SPRING-TYPES ON A GYMNASTICS REARWARD TUMBLING TAKE-OFF

William A Sands[1], Brent Alumbaugh[2], Jeni R McNeal[3], Steven Ross Murray[2], Michael H Stone[1]

[1]East Tennessee State University, USA

[2]Colorado Mesa University, USA

[3]Eastern Washington University, USA

Original article

Abstract

Gymnastics tumbling has occurred on large spring floor apparatuses for several decades. The spring floors have used a variety of elastic materials and designs to provide an increased take-off velocity and a forgiving landing surface. The purpose of this study was to assess the efficacy of a standard cylindrical spring (10.7 cm x 5 cm diameter, 9 coils) and a modified spring (10.7 cm, 5 cm widening to 6.7 cm diameter, 9 coils) in tumbling take-offs. Specifically, take-off foot contact durations and center of mass (COM) velocities from female gymnasts (14.8±2.8 y, 159.0±7.2 cm, 49.3±7.1 kg) were measured. Gymnasts performed two trials each of a round off, flic flac, to a layout rearward somersault on each spring-type attached to a tumbling strip (12.19m x 2.41m). Data were acquired via a Vicon™ kinematic system using 43 markers and 10 cameras at 200 Hz. Data were found to be reliable across trials. Analysis consisted of two, 2x3 repeated measures ANOVAs. The results showed no statistical differences between spring-types in terms of contact durations or COM component velocities. Spring-type design differences may lead to disparate spring constant and frequency effects, however, these effects of may be overwhelmed by the influences of gymnast skill, matting, carpet, and the wood and fiberglass laminate panels.

Keywords: *spring floor, somersault, jump, comparison.*

INTRODUCTION

The spring floor has been a mainstay of the floor exercise event for artistic men's and women's gymnastics for decades. The floor exercise apparatus is a 12m x12 m area that permits tumbling, balance, and other acrobatics in competition and training. The floor exercise apparatus in the United States has evolved in several stages: 1) a bare wooden gym floor, 2) a wooden gym floor with small mats strategically placed for skills, 3) a thin rubberized mat approximately one centimeter thick, 4) a wrestling-type mat, 5) a closed-cell foam mat with carpet, 6) a closed cell foam mat with vinyl covering, and 7) a spring floor using plywood laminate as the supporting surface with 5 or 10 cm (2 or 4 in) springs or foam blocks. The floor exercise supporting surface has transitioned from plywood to fiberglass-laminate panels and from 5 cm (2 in) to 10 cm (4 in) springs or foam blocks (Federation Internationale de Gymnastique, 2009). Internationally, the floor exercise apparatus has followed different design directions. For example, an early version included flexible wood panels separated in layers by staggered spacers that allowed the multilayer wood sections to rise and fall without interference (Figure 1).

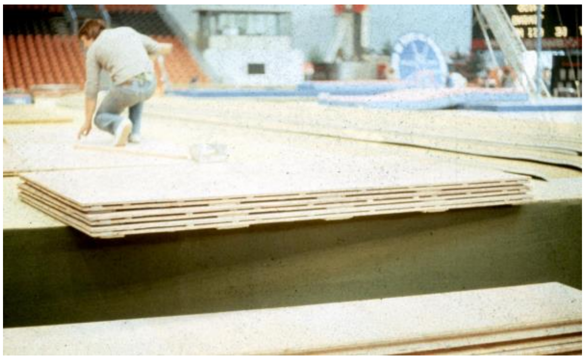

Figure 1. *Side view of an older spring floor design made completely of wood. Note the small spacers that are strategically placed such that no two spacers lie on top of each other thus giving the floor the ability to flex when loaded.*

The modern spring floor has been examined for various purposes in the past, particularly involving physical properties (Arampatzis & Bruggemann, 1999; Gormley, 1982; Paine, 1998; Peikenkamp, van Husen, & Nicol, 1999; Wilson, Neal, & Swannell, 1989). Less often, investigators have addressed the interactions between the gymnast and the spring floor (Arampatzis & Bruggemann, 1999; McNeal, Sands, & Shultz, 2007; Sands & George, 1988).

Characteristics investigated in the past have been the following:

- conical versus cylindrical springs (Gormley, 1982),
- foam block versus metal springs on somersault trajectory distances (Sands & George, 1988),
- dynamic loading response (Wilson et al., 1989),
- energy transfer from a somersault to a spring floor (Arampatzis & Bruggemann, 1999),
- optimal spring floor construction using 5cm springs and frequency response (Paine, 1998),
- leg stiffness control during jumping on an elastic surface (Arampatzis, Bruggemann, & Klapsing, 2000),
- a simulation of an area spring surface using a simple spring and mass damper model (Peikenkamp et al., 1999),
- kinematics of forward and backward twisting and non-twisting backward somersaults with electromyography (McNeal et al., 2007).

As the spring floor has evolved, elastic materials such as support panels and springs have been used to enhance the energy transfer of the legs to the spring floor and back to enhance flight phases and cushion landings. Elastic materials have increased the prominence of vibration and the influence of the frequency response of the floor to the athlete (Arampatzis et al., 2000). The concept of an ideal – tuning - of a floor area to achieve an optimal rebound response has been investigated and discussed for some time, primarily in running (Boyer & Nigg, 2006; McMahon, 1985; McMahon & Greene, 1978). Moreover, the ability of the participant to modify leg stiffness based on the running and jumping surface has also garnered attention (Arampatzis et al., 2000; Avela & Komi, 1998; Ferris & Farley, 1997; Grillner, 1972; Horita, Komi, Nicol, & Kyrolainen, 1996; Kuo, Wang, & Wang, 2002; Kyrolainen, Finni, Avela, & Komi, 2003; McHugh & Hogan, 2004).

One of the most important characteristics of the spring floor is the enhancement of the tumbling take-off in terms of trajectory height and rotation of the body about the feet and in the air. Trajectory height affords the gymnast ample time to complete his or her skills. The horizontal component velocity of the center of mass (COM) at take-off reflects the amount of a "trip-effect" that was obtained (Sands, 2011). The trip-effect leads to enhancing the somersault rotation of the gymnast. Paine and colleagues (Paine, 1998; Paine, Self, & Major, 1996; Self & Paine, 2001) studied the then current spring floor by cutting a rectangular section from a spring strip panel that fit over an in-ground force platform. As a part of his bioengineering doctoral dissertation, Paine experimented with spring floor modifications to "tune" the rebound characteristics of the spring floor by: adding springs (increasing stiffness), subtracting springs (decreasing stiffness), adding mass (changing the natural frequency), and using two different length springs (accommodating stiffness). Paine showed that a promising aspect of different length springs was the separation of elastic characteristics that could accommodate lighter loads, such as those from a small gymnast, and heavier loads, such as those from a larger more powerful gymnast. Previously and following Paine, the idea of an accommodating jumping surface has been studied by others (Gormley, 1982; Moritz & Farley, 2003; Wilson et al., 1989; Wilson, Swannell, Millhouse, & Neal, 1986). The basic premise is similar to that of adjusting the fulcrum on a diving board to match the approach and jump characteristics of the diver (Boda, 1993; Cheng & Hubbard, 2004; Jones & Miller, 1996).

The purpose of this study was to compare rearward somersault take-off characteristics as achieved from two types of coil springs attached to a spring tumbling strip. Specifically, this study sought to compare COM velocities (horizontal, mediolateral, vertical, and resultant), and foot contact phase durations (toe contact to heel contact, heel contact to heel departure, and heel departure to toe departure). It was hypothesized that there would be no statistical differences between the two spring floor-types. Our hope was that the modified spring would provide an obvious advantage to take-off parameters, but in keeping with a conservative approach, our hypothesis was - no difference.

METHODS

Subjects. Ten female gymnasts from the Grand Junction, Colorado area volunteered as subjects. All were experienced gymnasts with competitive abilities ranging from Level 7 to Level 10 within the USA Gymnastics Junior Olympic competitive hierarchy (USA_Gymnastics, 1994). Demographic information on the subjects is shown in Table 1. This study was approved by the Mesa State College and the East Tennessee State University Institutional Review Boards. All subjects and parents/guardians read and signed an informed consent/assent form in conjunction with data collection.

Table 1. *Subject Characteristics (N=10).*

Variable	Mean	SD	Minimum	Maximum	Range
Age (y)	14.8	2.8	11	19	8
Height (cm)	159.0	7.2	148.4	169.8	21.4
Mass (kg)	49.3	7.1	38.1	58.2	20.1

Equipment. The athletes performed a round off, flic flac (back handspring), back layout somersault on a tumbling strip (12.19 m x 2.41 m, 40 ft x 8 ft). The tumbling strip consisted of 2.41 m x 1.23 m x 0.013 m (8 ft x 4 ft x 0.5 in) panels of wood and fiberglass laminate. The tumbling strip was covered with continuous 12.8 m x 1.83 m x 0.05 m (42 ft x 6 ft x 2 in) foam matting (Figures 2 and 3). The matting was marked with red duct-tape near the take-off area 0.305 m (1 ft) from the edge. A start marking was used and represented the starting position of the athletes' tumbling sequences in their regular gym relative to their training gym floor exercise area and their regular foam pit landing area. A square of approximately 0.46 m was taped in red duct-tape as the take-off "target" for the feet of the gymnasts. This square was placed directly over the center of the take-off spring panel at the end of the tumbling strip and directly over the four central springs. Thirty-two springs were attached in 37 cm squares encompassing the bottom surface of each spring panel as per manufacturer instructions (Figure 4). The springs were provided by American Athletic Incorporated (ELITE™ Power Spring, Jefferson, IA, USA) and Weller Spring™ (King Bar Sports, Carefree AZ, USA, Patent No.: US 7,993,244 B2 Patent No.: US 8,337,368 B2), hereafter referred to as the cylindrical and modified springs, respectively.

Figure 2. *Spring strip as seen from the take-off end.*

The cylindrical spring was 10.7 cm in height and 5 cm in diameter with 9 coils. The modified spring was more complex in design, 10.7 cm in height, and 5 cm in diameter at the top and widening to a 6.7 cm diameter near the bottom. The modified spring used six coils on the upper spring section and three coils on the lower. Figure 5 shows the two types of springs and the fastening bracket.

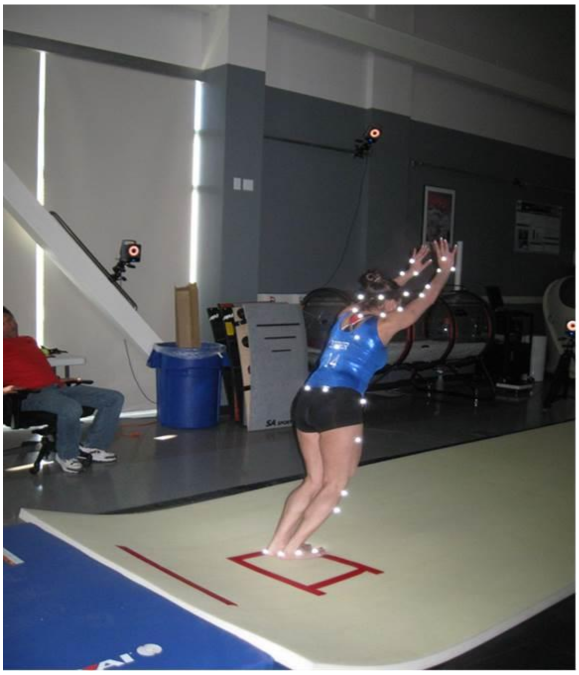

Figure 3. *Take-off area with taped markings.*

Figure 4. *Spring arrangement on the underside of the spring strip panel.*

Figure 5. *Modified spring on the left, spring end cap in the middle, and an cylindrical spring on the right.*

__Instrumentation.__ Kinematic 3D data capture and analyses were performed automatically by detection of 43, 14.5mm reflective markers using 10, Vicon™ T-Series T040 infrared cameras. The cameras were placed around the tumbling take-off area with four cameras on tripods low to the ground and six cameras on metal pipes mounted on the walls above the athlete. The Vicon-Nexus™ system was set to capture athlete marker motion at 200 Hz.

Forty-three reflective markers (14 mm diameter) were used for calibration as per the manufacturer's instructions and the Vicon-Nexus™ KAD-alike PlugInGait FullBody segment model included with the Nexus™ collection and analysis software was used to create the body segment model. Calibration of the subject required the use of four reflective markers on the medial aspects of the knees and ankles that were later removed for the tumbling trials. The marker set included the following: left front head, right front head, left back head, right back head, seventh cervical vertebrae, tenth thoracic vertebrae, superior notch of the manubrium, center of the sternum, right inferior-medial angle of the scapula, left shoulder, left upper arm, left elbow, left forearm, left ulnar wrist, left radial wrist, and left index finger at the metacarpal-phalangeal joint, left anterior superior spine, right anterior superior spine, left posterior superior spine, right posterior superior spine, left lateral knee, left medial knee, left shank, left lateral malleolus, left medial malleolus, left heel, left foot at the metatarsal-phalangeal joint of the second toe, right shoulder, right upper arm, right elbow, right ulnar wrist, right radial wrist and right index finger at the metacarpal-phalangeal joint, right thigh, right lateral knee, right medial knee, right shank, right lateral malleolus, right medial malleolus, right foot at the metatarsal-phalangeal joint of the second toe, and right heel. Figure 6 shows the marker set on an athlete. The COM model is included automatically within the Vicon-Nexus™ KAD-alike_PlugInGait_FullBody body segment model. The markers were attached to the appropriate anatomical landmarks with toupee tape. System calibration, camera checks, and monitoring of infrared noise from the separate images of each camera were performed and corrected prior to each data collection session.

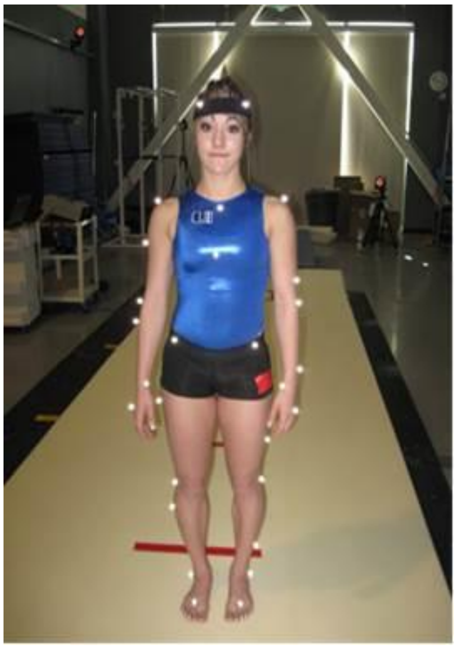

Figure 6. *Marker set for data capture. Note, the medial knee and ankle markers have been removed.*

__Procedures.__ The subjects came to the laboratory dressed in a leotard and spandex-type shorts (Figure 6). All subjects performed the tumbling trials in bare feet. Upon arrival, the subjects were measured for heights, masses, and queried for ages and birth dates. The subjects were then weighed, and several anthropometric measurements were obtained from the subjects' right sides as per the Vicon-Nexus^{TM} KAD-alike_PlugInGait_FullBody segment model requirements. The anthropometric measurements were as follows: leg length from the anterior superior spine to the medial malleolus across the patella, knee breadth, ankle breadth, shoulder "offset" measured from the acromion to the presumed center of the glenoid fossa, elbow breadth, wrist breadth, and hand thickness. All measurements were recorded in millimeters for later computer program entry.

Following anthropometric measurements, the reflective markers were placed on the appropriate anatomical landmarks. The subjects then stood still with feet apart and arms sideward for a "T-Pose" that was recorded and used to later calculate and verify body segment parameters and the calculation of the location of the whole body center of mass. Once adorned with reflective markers the subject was allowed an unlimited self-selected warm up period to familiarize herself with the tumbling strip, landing area, and the tumbling pass. Following warm up, the gymnast performed two or more round off, flic flac (back handspring), back layout somersault tumbling passes. The athletes had unexpected difficulty hitting the target area with their feet during their tumbling take-offs. It was determined that a take-off within approximately 30cm of the target area was sufficient in order to prevent fatiguing the gymnast through excessive tumbling trials seeking an exact target hit.

The spring floor panels were set up with modified springs on four panels and cylindrical springs on five panels. This approach was used to ensure that the full tumbling pass, except for the start of the run, was always performed on the spring floor spring-type of interest. In this way, the investigators could rapidly exchange the two types of spring panels so that the subjects only had to come to the laboratory once instead of twice. By maintaining the first panel the same, the alignment of the spring strip was easier and the time required to make the panel transitions was reduced. Reducing time during the transition was important to maintain the athlete's warm up. Athletes performed two or more familiarization tumbling passes following the panel transitions to ensure adequate warm up and step and take-off spacing. Assignment of the spring-type order of use was randomized and counterbalanced. Thus, after completion of two recorded tumbling trials the athlete rested for several minutes while the spring strip panels were reversed and realigned for a second set of two tumbling trials. The entire procedure required approximately one hour.

Data Analysis. Variable values were extracted from collected data of each recorded tumbling trial. Each trial was filtered using a Woltring filter (Woltring, 1985, 1986) following cropping, processing, and to determine the center of mass location for each frame. All paired variables were subjected to reliability analyses using an intraclass correlation. The mean of the two legs and trials was used for further data analyses. Descriptive statistics, 95% confidence intervals, and two repeated measures ANOVAs (RMANOVA, both dimensions), paired t-tests, effect sizes, and statistical powers were calculated to determine if there were differences between the kinematic variables between the two spring floor spring-types and to characterize the foot contact behavior of the gymnast during take-off (Cohen, 1988). RMANOVAs were calculated including: 2x3 (spring floor spring-type by foot contact durations) and a 2x3 (spring floor spring-type by velocity components of the COM at take-off). Type I error was controlled via the Bonferroni method (Sokal & James Rohlf, 1969).

RESULTS

Descriptive statistics for foot contact times and durations are shown in Table 2. Table 3 provides the center of mass take-off velocity values obtained at departure of the toes from the spring floor. Reliability analyses were conducted on the paired variables such as left and right legs and on trials one and two. Reliability was calculated using spreadsheet algorithms provided by Hopkins (Hopkins, 2000). Intraclass correlations were calculated across trials first and then from variable-to-variable. Intraclass correlations were also calculated across spring-types first and then from variable-to-variable. The results showed that all intraclass correlation coefficients for all variables exceeded 0.79, indicating excellent reliability (Lexell & Downham, 2005). There were no statistical differences with any variable pair (all P > 0.05). Sample distribution normality was tested with the Shapiro-Wilk test (O'Donoghue, 2012).

Table 2. *Descriptive Statistics – Foot Contact Durations.*

Variable	Spring Type	Mean	SD	95% Confidence Interval	
				Lower	Upper
Toe to Heel Duration (s)	Cylindrical	0.026	0.006	0.021	0.030
	Modified	0.024	0.004	0.021	0.027
Heel to Heel Departure (s)	Cylindrical	0.053	0.017	0.041	0.065
	Modified	0.058	0.012	0.050	0.065
Heel Departure to Toe-off (s)	Cylindrical	0.070	0.046	0.036	0.103
	Modified	0.051	0.019	0.037	0.064
Total Contact (s)	Cylindrical	0.148	0.046		
	Modified	0.133	0.017		

Table 3. *Descriptive Statistics – Take-off Velocities.*

Variable	Spring Type	Mean	SD	95% Confidence Interval	
				Lower	Upper
Mediolateral (V_x m• s^{-1})	Cylindrical	0.04	0.18	-0.86	1.67
	Modified	0.07	0.19	-0.67	2.09
Horizontal (V_y m•s^{-1})	Cylindrical	3.04	0.48	2.69	3.39
	Modified	3.22	0.47	2.89	3.56
Vertical (V_z m•s^{-1})	Cylindrical	4.29	0.62	3.85	4.74
	Modified	4.24	0.49	3.89	4.59
Resultant (V_R m•s^{-1})	Cylindrical	5.29	0.57		
	Modified	5.35	0.48		

Three foot contact phases were identified, toe contact to heel contact, heel contact to heel departure, and heel departure to toe departure. All athletes touched their heels to the spring floor matting. A 2 (springs) x 3 (foot contact phases) RMANOVA was calculated. The analysis violated the sphericity assumption resulting in use of the Greenhouse-Geisser adjustment of degrees of freedom. The analysis showed no statistically significant within subjects main effects for spring-type ($F_{(1,9)} = 1.03$, $p = 0.34$, $\eta^2_{partial} = 0.10$, power = 0.15), or the spring by contact phase interaction ($F_{(1.3,11.7)} = 2.0$, $p = 0.19$, $\eta^2_{partial} = 0.18$, power = 0.28). There was a statistically significant main effect for foot contact phase times ($F_{(1.14,10.24)} = 10.72$, $p = 0.007$, $\eta^2_{partial} = 0.54$, power = 0.87). Contrast procedures showed that the first phase was statistically different from the third phase ($F(19) = 20.7$, $p = 0.001$, $\eta^2_{partial} = 0.70$, power = 0.98). Ninety-five percent confidence intervals for the foot contact phase data are shown in Table 2.

The velocity components (mediolateral (x), anterior-posterior (y), vertical (z)) of the COM at take-off were analyzed via a 2 (springs) x 3 (COM velocity components at take-off) RMANOVA. The analysis showed no statistically significant within subjects main effects for spring-type ($F_{(1,9)} = 1.65$, $p = 0.23$, $\eta^2_{partial} = 0.15$, power = 0.21), or the spring by velocity components interaction ($F_{(2,18)} = 2.2$, $p = 0.14$, $\eta^2_{partial} = 0.19$, power = 0.39). There was a statistically significant main effect for velocity components ($F_{(2,18)} = 259.0$, $p < 0.001$, $\eta^2_{partial} = 0.97$, power = 1.0). The main effect for velocity components was expected based on the directions of these vectors. Ninety-five percent confidence intervals for the velocity components data are shown in Table 3.

Paired variables for the total floor contact times and the COM resultant velocities between spring floor-types were examined using matched pairs t-tests. The mean values for each variable by spring floor-type are shown in Tables 2 and 3. The total foot contact times did not show a statistical difference between floor-types ($t_{(9)} = 1.02$, $p = 0.34$, $\eta^2 = 0.009$, 95% CI: -0.019s to 0.050s). The resultant velocity of the COM at take-off did not show a statistical difference ($t_{(9)} = -0.8$, $p = 0.44$, $\eta^2 = 0.006$, 95% CI: -226.3m•s^{-1} to 107.7ms^{-1}). Pearson correlation coefficients of the relationship between total foot contact times between the spring-types was $r = 0.05$, $p = 0.88$), and the resultant velocity of the COM between spring-types was $r = 0.91$, $p < 0.001$).

DISCUSSION

The goal of this study was to characterize the differences between spring floor-types characterized by different coil springs by assessing foot contact times and COM velocities at take-off. Although there were statistical differences between the durations of foot contact phases, and between the velocity components of the COM, there were no statistically significant differences between spring floor-types. In addition, the statistical correlation between COM resultant velocities across spring types showed that the velocities were highly similar. Moreover, effect sizes and confidence intervals supported the hypothesis test statistics. These analyses indicate that in spite of a clever spring design, the modified spring did not change or enhance performance relative to foot contact durations and take-off velocities. The cylindrical spring and the modified spring do not appear to differ in their influence on the gymnast's rearward somersault tumbling take-off.

Gymnastics performance analysis rarely considers the interaction of the gymnast and the apparatus. This simple study investigated whether two different types of springs resulted in differences in take-off performance. Tumbling take-offs have been shown to reveal differences in gymnast ability via anterior-posterior and vertical velocity components (Burgess & Noffal, 2001). Engineering approaches (Paine, 1998) and computer modeling (King & Yeadon, 2004a, 2004b) have been used to characterize the spring floor, perhaps because of the ease of maintaining experimental controls (Federation_Internationale_de_Gymnastiqu e, 2009; Sands, 2000).

Although this study did not show enhanced take-off performance based on spring-type, the influence of the spring floor on performance and safety remains a possibility. Other performance factors may have a more dominant influence on take-off parameters. Gymnasts may alter their muscle stiffness properties as a result of practicing on different surfaces, much as runners alter their leg stiffness to cope with differing terrains (Arampatzis et al., 2000; Arampatzis, Bruggemann, & Klapsing, 2001; Günther & Blickhan, 2002; Kuitunen, Ogiso, & Komi, 2011; McNeal et al., 2007). Gymnasts' skill and strength may confound simple relationships by virtue of the ability of a gymnast to jump effectively during the take-off regardless of the spring floor by skillfully altering lower extremity muscle stiffness. Historically, gymnasts have performed rearward somersault take-offs on road pavement, sidewalks, and other surfaces that provide little or no rebound springiness. Of course, no one would advise regular use of harsher take-off and landing areas, but the floor exercise apparatus should be tuned properly such that the spring floor acts in synchrony with the gymnast. The present study indicates that spring characteristics may not be a powerful variable for controlling spring floor behaviors.

The future should bring increased emphasis on the identification of those factors that enhance tumbling skill performance while being sensitive to safety demands via injury prevention. Specifically, future investigations should address the mechanical behaviors of the various springs, matting, carpet, panels, and sub-flooring such as the competitive podium. Perhaps unfortunately, the specific performance context of spring floor in competition will be complicated by the interaction of many variables. Finally, the gymnast's ability to manage his/her lower extremity stiffness during the decisive moment of take-off should be explored and a reasonable range of stiffness management tactics should be identified for differing ages, sizes, and ability levels.

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Corresponding author:

William A Sands, PhD, FACSM, NREMT, WEMT, CSCS
Professor, Department of Exercise and Sport Science
East Tennessee State University
Johnson City, TN 37601
719.313.8915
sandsw@etsu.edu
wmasands@hotmail.COM