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**ATINER's Conference Paper Series**
**FIT2012-0123**

# The Position of the Center of Mass during the Support Phase of Forward Somersaulting Skills on the Trampoline

**S. Alan Lephart, Ph.D.**
**Assistant Professor**
**Exercise Science Department**
**Fort Lewis College**
**USA**

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209
Email: info@atiner.gr URL: www.atiner.gr
URL Conference Papers Series: www.atiner.gr/papers.htm

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ISSN **2241-2891**
6/09/2012

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This paper should be cited as follows:

**Lephart, S. A.** (2012) "**The Position of the Center of Mass during the Support Phase of Forward Somersaulting Skills on the Trampoline**" Athens: ATINER'S Conference Paper Series, No: FIT2012-0123.

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**S. Alan Lephart, Ph.D.**
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**Abstract**

One popular theory regarding the generation of angular momentum for forward somersaulting suggests that placing the center of mass (COM) in front of the base of support with the supporting surface pushing vertically upward provides the torque required to initiate rotation. Another theory suggests that the COM remains over the base, and that the feet push downward and forward into the supporting surface to provide the torque causing rotation. This study used slow motion film to analyze the COM motion during forward somersaulting skills on the trampoline to determine which theory might be correct. Analysis of five expert performances indicated that the COM always remained over the base of support throughout the take-off, and that the torque was generated by pushing forward and downward with the feet into the supporting surface. In every performance, the performer developed a forward velocity before landing after a preliminary bounce or immediately after contact with the surface, which continued until just prior to take-off, at which time a sharp backward acceleration occurred. This acceleration arrested the forward motion and provided the torque that caused rotation, allowing the performer to complete the skill with little horizontal motion during the performance. A sixth performance, deliberately attempting to perform the skill by placing the COM in front of the base, showed that although it is possible to generate some angular momentum in this manner, this was not a viable method in terms of acceptable performance because of reduced height and excessive horizontal displacement during the performance.

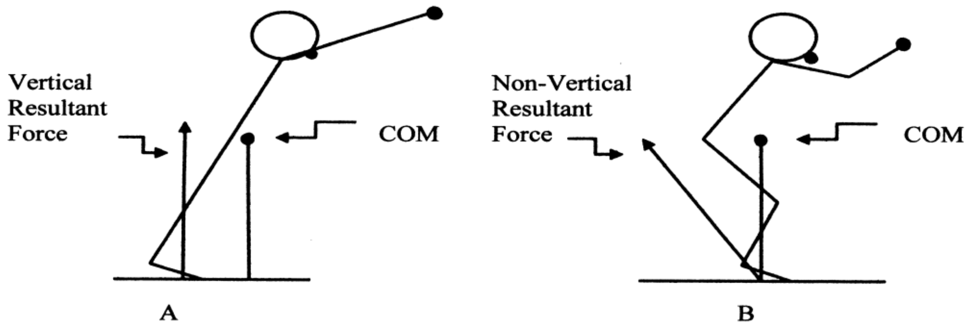
**Contact Information of Corresponding author:**

## Introduction

The trampoline is a mechanism designed to allow the performer to obtain height in order to perform complex gymnastic maneuvers in the air. The mechanical analysis of such skills is important in understanding the means of performing them. Forward somersaulting skills are common in this sport, as they are in other gymnastic events and in diving. In order to initiate angular momentum, it is necessary to apply a torque to the body while still in contact with the trampoline bed. This can be done in two distinct ways or by combining elements of the two methods.

One commonly suggested method of providing torque is to place the center of mass (COM) in front of the base of support, the feet (Bunn, 1972; Hall, 2012; Hay, 1978; Simonian, 1981). This means that any vertical force from the trampoline applied behind the COM will provide a torque to generate forward rotation (Figure 1 A). Theoretically, the force is directed vertically upward, thus preventing any forward or backward movement of the COM. However, unless the COM is appreciably forward of the base of support, the radius of the force moment will be insufficient to produce the necessary angular momentum to complete the skill. Conversely, if the COM is too far forward of the base of support, forward acceleration will also occur. In any case, this concept cannot explain the initiation of rotation in such skills as inward and reverse somersaulting in diving.

**Figure 1.** *Two Theoretical Methods of Generating Torque in Forward Somersaulting Skill*




A second suggested method is to keep the COM directly over the base of support and push downward and forward with the feet (Zatsiorsky, 2002) as the trampoline accelerates the performer vertically upward. The reaction of the forward push of the feet results in a force from the trampoline being applied horizontally backward producing the torque that causes forward rotation (Figure 1 B). The difficulty in this explanation is that this backward force should also make the performer accelerate backward, which should result in backward travel during the execution of the somersault. However, good performers always appear to move vertically up and down without perceptible horizontal motion either forward or backward.

Observation indicates that the head, arms, and upper torso all rotate forward as the performer is accelerating vertically. By the law of conservation of angular momentum, this implies a forward push with the feet against the trampoline bed.

*Purpose of this Study*

This study will attempt to determine the position of the COM throughout the preliminary bounce, the period during contact with the trampoline bed, and during the actual execution of the somersaulting skill in the air. Since the trampoline is the only horizontal force acting on the performer, any changes in the horizontal velocity of the COM will reflect the horizontal force applied by the trampoline against the feet (inverse dynamics).

It is the hypothesis of the study that the performer will develop a forward velocity either during the preliminary bounce or during the landing prior to executing the skill, and that the forward push by the feet into the trampoline will result in a reduction of that velocity to nearly zero during the performance of the trick. Only in this way, can there be sufficient torque to produce rotation without noticeable horizontal movement of the COM.

*Working Definitions*

This study uses the following working definitions:

1. Prebounce – The bounce prior to the actual performance of the skill.During this period, the performer has no contact with the trampoline.
2. Bedwork – That period in which the performer first contacts the trampoline after the prebounce until he breaks contact with the trampoline in order to perform the actual skill.
3. Landing – That period of the bedwork beginning from the time of first contact with the bed after the prebounce until the bed reaches its deepest depression
4. Take-off – The period of the bedwork beginning from the deepest depression of the bed until the performer breaks contact with the trampoline bed to perform the actual skill.
5. Trick – The bounce during which the somersaulting skill is performed. During this period, the performer has no contact with the trampoline.

*Methods*

To test the hypothesis, six performances of forward somersaulting skills were analyzed. Four performers were involved, one Australian trampoline champion, one national level competitor, a talented physical education student, and a trampoline coach. The first four performances, two by each of the first two performers, were forward two-and-three-quarter somersaults. The fifth performance was a double forward somersault by the physical education student and the final performance was a one-and-three-quarter somersault by the coach. The last performance was a special case in which the coach was asked to attempt to perform the skill by keeping his COM in front of his feet throughout the bedwork phase of the performance.

The performances were filmed at a nominal camera speed of 64 frames per second but the actual speed, when tested, was between 53 and 58 frames per second. While the camera speed varied from performance to performance (depending on how much film was on the take-up spool), it was reasonably consistent within any given performance. In the final analysis, it was found that analyzing every third frame during both the prebounce and the trick was sufficient to establish the path of motion during those phases, but all frames were used during the bedwork because of its relatively short duration.

Each frame was analyzed to locate the COM using a fourteen-segment model based upon the data from Dempster's classic study (Dempster, 1955). A balance board was used to increase the accuracy of the trunk COM location when bent forward in a tuck position. The preliminary bounce was used to determine true camera speed by plotting the vertical position of the COM and adjusting the nominal camera speed to give the resulting parabola of motion an acceleration equal to that caused by gravity (– 980 mm/s$^2$). The preliminary bounce and trick horizontal motions were used to determine whether the COM was accurately located. If correctly located, the COM follows a straight-line path horizontally and the data points would all lie within the range of error in COM location.

Once the COM position was located in each frame, the positions were plotted to show the COM path in both the vertical and horizontal directions throughout the entire performance. The data were also divided into prebounce, bedwork, and trick for mathematical analysis. Linear regression was used for the horizontal motion during the prebounce and the trick. The vertical motion during these same two phases was fitted using a parabolic curve. The vertical motion during the bedwork was represented by a quartic equation. This was based on a preliminary study of trampoline forces performed by the author some years ago (Lephart, 1971). The horizontal motion during the bedwork was represented by a fifth order polynomial to allow joining it to the prebounce and the trick, using constraints at the points where these curves naturally intersected.

The position of the base of support (the feet in contact with the trampoline) was recorded throughout each performance so that the position of the COM relative to the base of support could be determined.

*Results and Discussion*

The mean filming rate for all performances was 56 frames per second ± 1.7, and the mean absolute error in locating the COM was 13 mm. ± 1. The length of the base of support (feet) varied slightly from performer to performer with a mean value of 268-mm. ± 11. A summary of recorded data regarding the COM relative to the trampoline surface and to the base of support is shown in Table 1.

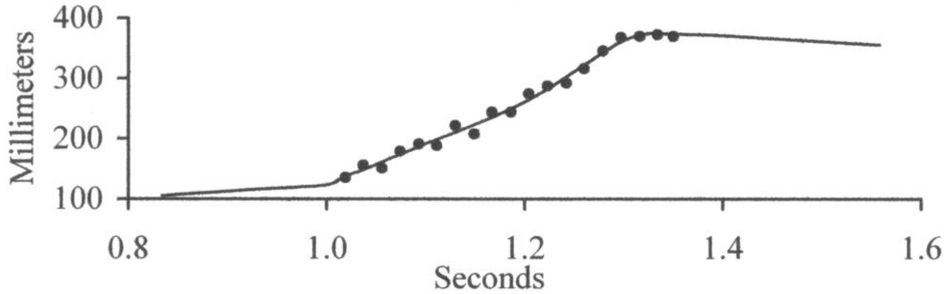
**Table 1.** *Statistics of the COM Relative to the Trampoline Surface and Base of Support*

| Statistics in Order of Occurrence | Performance | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Prebounce Max. Hgt. (mm) | 2297 | 2553 | 2789 | 2956 | 2123 | 1921 |
| Hor. Landing Vel. (mm/s) | 43 | 20 | 295 | -115 | 396 | -987 |
| Vert. Landing Vel. (mm/s) | -4930 | -5193 | -6042 | -6098 | -4784 | -4395 |
| Landing Angle (deg) | 90.5 | 90.2 | 92.8 | 88.9 | 85.3 | 77.4 |
| Landing Inflex. Hgt. (mm) | 947 | 913 | 836 | 941 | 853 | 804 |
| Min. Bedwork Hgt. (mm) | 313 | 429 | 190 | 161 | 307 | 201 |
| Take-Off Inflex. Hgt. (mm) | 846 | 899 | 953 | 990 | 955 | 934 |
| Hor. Take-Off Vel. (mm/s) | -36 | -58 | -528 | 130 | 275 | 213 |
| Vert. Take-Off Vel. (mm/s) | 4806 | 5299 | 6430 | 6249 | 4971 | 4673 |
| Take-Off Angle (deg) | 90.4 | 90.6 | 94.7 | 88.8 | 86.8 | 87.4 |
| Trick Max. Hgt. (mm) | 2136 | 2771 | 3208 | 3163 | 2491 | 1921 |
| *Hor. Landing Pos. (mm) | -45 | 37 | - 56 | 72 | - 20 | 397 |
| **Hor. Take-Off Pos. (mm) | -38 | -46 | -40 | - 58 | - 25 | 70 |

Note: The *Horizontal Landing Position is the COM position relative to the heel and the **Horizontal Take-Off Position is relative to the toes.

The data plot shown in Figure 2 represents the horizontal displacement of the first performance during the bedwork. An upward slope of the data indicates a forward movement (positive horizontal velocity) and a downward slope represents a backward movement (negative horizontal velocity) during each part of the performance. Both the prebounce and the trick horizontal displacements (Figure 2) are represented by straight lines since there are no horizontal forces acting during these phases of the performance.

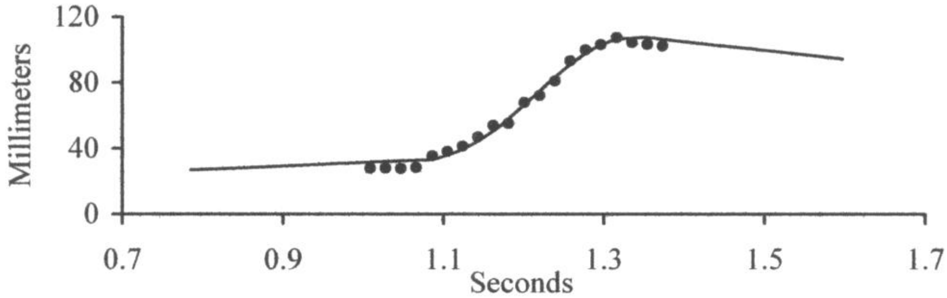
**Figure 2.** *Horizontal Displacement of the COM of Performance 1*




The extended lines on this graph represent the horizontal COM path coming into the landing and leaving the trampoline after the take-off, respectively. The middle portion shows the horizontal displacement during the bedwork.

Figures 3 through 5 represent this same motion in each of the three subsequent performances.

**Figure 3**. *Horizontal Displacement of the COM of Performance 2*




Since the premise of this study is based on the horizontal force being applied to the feet (and consequently to the COM) by the trampoline, the change in horizontal velocity of the COM during the bedwork is of vital interest. The horizontal velocity is represented by the gradient of the curve at any given point and the acceleration by the curvature of the displacement.

It is obvious from all four performances that the COM begins to move or is already moving forward during the landing (indicated by the upward slope of the data) and that in every case it accelerates backward during the final stages of the take-off. In the first two performances, the performer jumps slightly forward during the prebounce and moves slightly backward during the trick (Australian champion performances). Though the third performance (the national competitor), had slightly greater horizontal movement, the pattern of jumping forward in the prebounce and backward during the trick was the same as the first two performances. Even though the fourth performance (the national competitor) shows that the performer had a slight backward velocity in the prebounce, it was quickly arrested upon contact with the trampoline and the COM was moving forward very early during the landing (≈ 1.2 to 1.5 seconds). The forward movement was not completely arrested by the forward push of the feet in this performance, but the performer traveled forward only about 100 mm during the trick. From the curvature toward the end of the take-off of each of these performances (≈ 1.4 to 1.6 seconds), it can be seen that there is a negative horizontal acceleration as the feet push forward into the trampoline bed during this time.

**Figure 4.** *Horizontal Displacement of the COM of Performance 3*

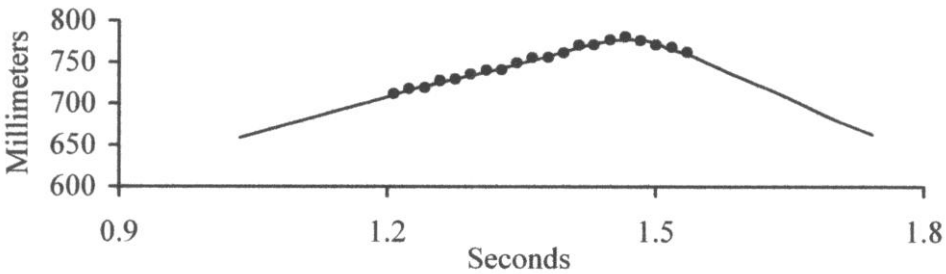
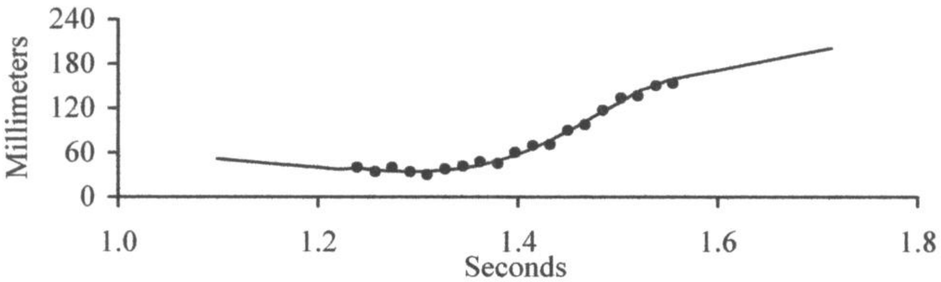
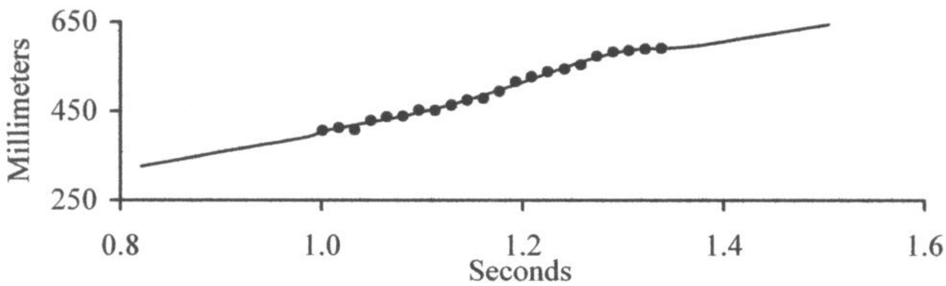



**Figure 5.** *Horizontal Displacement of the COM of Performance 4*




The fifth performance (Figure 6) was somewhat different. In this case, the performer (the student) moved forward in the prebounce and continued to move forward at almost the same velocity during the trick, although there was a slight reduction in forward velocity during the take-off (≈ 1.3 to 1.5 seconds)

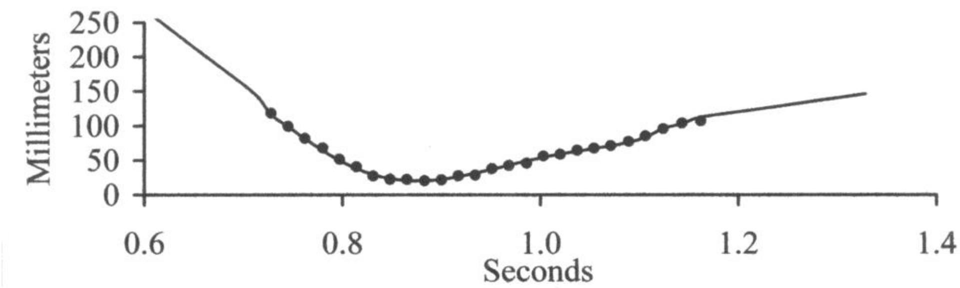
**Figure 6.** *Horizontal Displacement of the COM of Performance 5*



It is important to note that in each of these performances, the COM was never outside of the base of support (the feet) during the take-off. This led to the question of whether placing the COM in front of the base of support was really a viable method of producing torque. To answer this question, the coach, an experienced performer, was asked to try to perform a forward somersaulting skill using only this method to produce torque. Because considerable horizontal movement might be expected, the performer chose to perform a simpler skill, a forward one-and-three-quarter somersault, to reduce the risk of injury.

As can be seen from the graph, the horizontal motion of the COM was extreme (Figure 7). The performer traveled backward almost one meter during the prebounce, landing with his feet well behind the COM. He leaned forward throughout the bedwork to try to keep the COM in front of the feet and traveled forward about 350 mm. during the trick.

**Figure 7.** *Horizontal Displacement of the COM of Performance 6*




A detailed look at the bedwork of the performance showed, however, that there was still a very slight acceleration backward during the take-off, although it was not sufficient to stop the forward motion during the trick.

The performer made every effort to keep the COM in front of the toes throughout the bedwork and measurements showed that he was able to do so. The COM was 137 mm in front of the toes at landing and gradually moved backward to a position just 70 mm forward of the toes at the take-off of the trick. The performance was, however, not one that any accomplished trampolinist would consider "acceptable" because of the large amount of horizontal motion in both the prebounce and the trick, and the relatively low height developed in both of those phases.

It was clear from the data that although the good performers appeared to be bouncing vertically, this was not actually the case. In every performance, there was slight horizontal movement during the prebounce (usually forward) and the trick (usually backward). This movement was virtually unnoticeable without film analysis in the better performances. The three better performances in this study (1, 2 and 4) landed (prebounce) and took off (trick) at more nearly vertical angles than the other performances. All performances regardless of the landing angle from the prebounce, moved horizontally forward during the bedwork and applied a forward force with the feet to arrest, or at least reduce, the forward motion during the take-off. With close inspection, a slight forward push with the feet was evident even in the final performance (number 6).

The forward push with the feet provided torque to produce forward rotation during the trick. In all performances, the forward push with the feet occurred late during the take-off when the performer was nearing that point in the upward motion when the acceleration was changing from positive to negative as gravity became equal to the upward force of the trampoline bed (the take-off inflexion point in the displacement curve).

*Conclusion:*

It is apparent that in good performances of forward somersaulting skills, the torque results from the arresting of forward motion generated during the prebounce or landing. This has also been reported in tumbling on mats (Zatsiorsky, 2002).

The COM is never in front of the base of support in good performances on the trampoline, and this method is simply not a viable means of producing torque. The pattern of the horizontal motion during the bedwork confirms that there is a forward push with the feet against the trampoline bed during the take-off, which reduces or reverses any forward motion and provides the torque necessary to produce forward rotation during the trick. Since the COM is never forward of the base of support in good performances, the theory that forward rotation is caused by placing the COM in front of the base of support during the take-off is simply untenable.

The implication for teaching these skills, as with any forward somersaulting skill, is that the performer should be encouraged to move slightly forward prior to the skill and to push downward and forward during the latter stage of the take-off to arrest forward motion and to produce the torque necessary to complete the rotation. This forward thrust with the feet should be rapid and should occur late in the take-off, just prior to leaving the supporting surface. Under no circumstances should a performer be encouraged to lean forward to initiate rotation since this contributes little torque and greatly increases the risk of traveling forward during the performance of the skill.

It is recommended that other skills, such as backward somersaults, and forward somersaulting skills in other contexts (gymnastics, diving, etc.) should be analyzed to determine if a similar mechanism for producing angular acceleration applies.

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