
COVER SHEET

Title: Biomechanical Research in Artistic Gymnastics

Running Head: Research in Gymnastics

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Abstract

Biomechanical research regarding artistic gymnastics has grown substantially over the years. However, most research is still skill oriented with few attempts for generalization. Consequently, our understanding of the principles and bases of the sport although improved, is still marginal with gaps in knowledge regarding technique attributes that can transcend throughout the sport. For that reason, this review commences with an attempt to identify important performance variables contributing to successful performance. The review is presented in clusters of work in similar apparatuses culminating in Tables offering an “at a glance” summary of knowledge in the cluster. The last section of the review attempts to give some direction to future biomechanical research in gymnastics in issues relating to data collection (2-D vs. 3D, image size, framing rate) and analysis (descriptive vs. explanatory, simulation and optimization, statistical issues, etc.).
Introduction

In contrast to most other sports which are comprised of a few or even a single activity, artistic gymnastics includes multiple events—six for men, four for women—and, in each event gymnasts perform routines comprised of many skills. These skills could and, in some cases, have been the subject of several research papers with the end result being quite large a body of gymnastics research. The task of providing all-inclusive information in a single article is challenging. For example, Figure 1 illustrates a model of factors determining the postflight score awarded to gymnasts in vaulting. Even a cursory view of this (non-exhaustive) model of (only one phase of) vaulting challenges the notion of anyone being able to claim a (complete) “understanding” of the sport of gymnastics—with its hundreds of skills and possible models. To contribute to the process of “understanding”, review articles have been published previously (Brüggemann, 1994; Prassas, 1995a Prassas, 1999a; Sands et al., 2003). This article continues and builds on the previous work by first attempting to identify the scientific bases for identifying variables that are important to gymnastics performance from a biomechanical perspective. It then sets the stage for future research by providing an overview of current knowledge. This is followed by a discussion of factors to be considered by researchers in the context of the methodological challenges pertaining to gymnastics research.
Important Performance Variables from a Biomechanical Perspective

A shift in gymnastics judging involving an “open code” may occur in the future. If adapted, scores will not be constrained to 10.0 points and competitors will be able to set a “world record” in gymnastics by a combination of exceptional execution and difficulty. The details of how this new approach may be implemented are being debated (Personal Communication, USA Gymnastics).

However, according to existing competition regulations, the maximum attainable score in gymnastics is currently 10. In most apparatuses, this score is awarded by 2 juries of officials. The first sets the start value on the basis of difficulty, special requirements, and bonus points while the second evaluates the exercise presentation on the basis of technique and position (FIG, 2002). In order to earn a high score, gymnasts must perform difficult routines with high accuracy and proper technique. Biomechanics is well suited to examine, describe, develop, and improve technique. Although there is a multitude of variables influencing success in the sport, including psychological and physiological factors, biomechanical considerations, as reflected in technique (proper or not), are crucial. With minimal exceptions, gymnasts must develop the following technique attributes that apply to the great majority of skills/apparatuses:
**Ability to gain height**: One of the most important ways for a gymnast to distinguish his/her performance is via height of flight, for example postflight height in vaulting. Height of flight may indirectly affect the judges’ score (for example, a gymnast may be rewarded for virtuosity in airborne skills executed with greater height). Height in any apparatus/skill is determined by the takeoff vertical velocity. In vaulting and tumbling skills, vertical velocity is directly related to the ability of the gymnast to utilize horizontal energy generated during the run and to utilize the springboard and elastic properties of the floor to develop vertical momentum. This is only partially true in tumbling skills performed on the balance beam where height is not only the result of this conversion, but to a greater extent, also, of the vertical jumping abilities of the gymnasts. On release/re-grasp skills performed on the horizontal bar and uneven/parallel bars, as well as dismounts from these apparatuses and from the still rings, vertical velocity—and therefore height—is proportional and depends mostly on the ability of the gymnast to correctly partition the angular momentum of the preceding swing into linear and angular motions appropriate to the linear and rotational requirements of the skill in question (Cheetham, 1984; Brüggemann et al., 1994; Holvoet et al., 2002).

**Ability to rotate**: The majority of gymnastics skills include some type of somersaulting, twisting, or both. In airborne rotational skills (included in floor exercise, vaulting, uneven/parallel bars, horizontal bars, and still rings dismounts) the gymnast rotates about his/her center of gravity (CG). Of paramount importance
in successfully performing rotational skills is the ability of gymnasts to develop
and/or control the somersaulting and/or twisting angular momentum. Angular
momentum is determined by two factors: moment of inertia—which increases as
gymnasts assume a more stretched or “layout” body configuration—and angular
velocity, the amount of spin the body or body part possesses. The simplest, and
probably the most common method of creating rotation in gymnastics come from
an eccentric (off-CG) push of the legs or arms against the supporting surface. This
force couple produces a torque that initiates a turn of the body around its CG that
continues once the athlete becomes airborne and it is perhaps the most commonly
used mechanism for producing multiple twisting somersaults in gymnastics due to
the time constraints of typical gymnastics flight times.

A second method of producing rotation, this time more commonly seen in
somersaulting skills is called a “trip effect” (Gluck, 1982). The basic idea is quite
simple: if a gymnast is running forward for example and plants both feet suddenly
and quickly, the gymnast’s body will rotate about his/her fixed feet and thus begin
to somersault. If the gymnast skillfully jumps during the period of time while the
feet are fixed, then the gymnast may add enough height and flight time to allow
him/her to somersault one or more total revolutions and land back on his/her feet.
A simple way to increase the amount of gymnast’s somersault rotation is by
moving horizontally faster so that the trip effect results in a more rapid rotation.

In airborne rotational skills such as in tumbling, vaulting, and dismounts from
apparatuses, the gymnast must takeoff or launch from the apparatus with an
appropriate “total” angular momentum for the skill. As stated previously, physical laws dictate that this momentum remains the same from takeoff to landing or re-contact with the apparatus. This momentum conservation principle, the fact that the “total” angular momentum is made up of the sum of the angular momenta of the gymnast’s segments, and the fact that angular momentum reflects the product of moment of inertia and angular velocity may be utilized in a variety of ways:

1. **To generate twist.** Although gymnasts may utilize other mechanisms to generate twists—as when still in contact with the apparatus—there is a definite advantage in generating twists *after* taking off from the apparatus. Figure 2 depicts a double back layout somersault with two twists produced by asymmetrical motion of the arms. The main advantage of this technique is that the twist may be safely removed before landing by reversing the action of the arms (Yeadon, 1999; Yeadon and Kerwin, 1999). The disadvantage of this technique may lie in its limitation in the rate of twisting produced. Gymnasts are usually constrained by limited flight time that makes airborne twists less likely to produce multiple twisting somersaults than twists generated from the contact surface. However, in practice, gymnasts generally use a combination of methods to perform twisting somersaults.

Insert Figure 2 about here
2. **To transfer spin from one body part to another.** A practical application of the ability to “transfer” angular momentum between body parts is the case when a gymnast, realizing that he/she may over rotate, quickly spins a body part (usually the upper extremities) *in the direction* of (whole body) rotation. This “transferring” action of angular momentum from the body to the body part(s) slows down the rotation of the gymnast's body, increasing the possibility of a successful landing.

3. **To increase/decrease rotation by altering body configuration:**
   Successful performance of a rotational skill requires the correct amount of angular momentum—which increases as the number of somersaults/twists increases and/or as the body configuration increases from a tight tuck (small moment of inertia) to full layout (large moment of inertia). Angular momentum is created or generated when the gymnast is in contact with a supporting surface. Once airborne, gymnasts can alter the speed of rotation by changing body configuration since the total angular momentum remains constant. If a gymnast's takeoff angular momentum is not sufficient to complete a predetermined skill, then he/she may—if physically possible—tighter tuck. This increases the rate of spin and the chances of completing the predetermined rotations. Conversely, the chances of successful landings increase if the gymnast’s somersault and twist spin rates decrease.
immediately prior to landing. Thus, gymnasts usually “open up” before landing to decrease the rate of spin.

Ability to swing: Gymnasts employ swings in a variety of movements including kips and casts. Moreover, gymnasts swing from a variety of body parts; hands, feet with hands, upper arms, and shoulders. Gymnasts swing in pendular fashion as in swinging from the hands with a straight body, and in more complex ways with multiple pendulums such as when swinging on still rings. A still rings swing involves an entire system of pendular movement that may be composed of several “sub”-pendulums including the legs, the trunk, and the rings and cables. Not only the magnitude of the total swing, but the interaction of the various subsystems or sub-pendulums acts to enhance or detract from gymnastics performance. Although swings are important in these type of movements and as links between balance movements on still rings and parallel bars, they become of paramount importance as preparatory maneuvers for release/regrasp skills and dismounts from the high bar, uneven and parallel bars, and still rings. With the understanding that similarities and differences exist among all swing types, we will discuss swings leading to release/regrasp skills and dismounts.

1. Factors affecting swing: Three factors affect swinging: the friction between the gymnast’s hands and the apparatus, air resistance, and the torque of his/her weight. In general, friction and air resistance retards the circling
motion whereas the torque produced by body weight promotes speed in the
downswing and opposes it on the upswing. Depending on the particular
“gripping” and direction of rotation, friction may make the gymnast’s grip
“stronger”. “Gripping” refers to the nature of how the gymnast grasps the bar,
rail, ring or pommel. In gymnastics, the term “grip” can be used to describe
a hand grasping the apparatus or the way in which the hand grasps the
apparatus. Gymnasts use various grips (types of hand grasps) to perform
different skills. In fact, at times the grip alone may describe the skill, such
as an overgrip, elgrip, or undergrip giant swing. All are giant swings and
vary by direction and the way the gymnast grasps the bar or rail. Figure 3
depicts a giant swing. If the gymnast begins the downswing from a still
position (position 1 in Figure 3) and remains rigid throughout, he will “stall”
during the upswing due to the effect of friction and air resistance. If starting
from a non-still position, the gymnast may complete and continue a full
rotation, but with less angular momentum than at the beginning. To
counteract these effects the gymnast must decrease on the upswing the
moment of inertia and, thus, the torque produced by the weight by
decreasing the weight’s moment arm, the perpendicular distance from the
center of rotation (high bar) to the line of action of the weight (see d, Figure
3).

Most gymnasts are not concerned with just completing rotations.
Their aim is to be able to increase/attain the necessary angular momentum
for a specified release/regrasp skill or dismount. Depending on the apparatus, gymnasts may employ a variety of techniques to achieve this purpose. An obvious technique employs as much “elongation” as possible or permitted by the apparatus constraints (e.g., the low rail of the uneven bars) on the downswing, followed by flexion/extension at the hip/shoulder joints on the upswing. The prescribed downswing action effectively increases angular momentum by increasing the angular impulse of the weight, whereas the shoulder/hip actions in the upswing reduce the loss of angular momentum by decreasing the moment of inertia of the gymnast about the axis of rotation. “Tapping” actions are employed by gymnasts to take advantage of the length tension relationships described in biomechanics literature and bar or rail elasticity.

Insert Figure 3 about here

2. **Traditional vs. scooped techniques.** Kerwin (1999) described two distinct types of swings aimed to increase angular momentum, the “traditional” and the “scooped” (or “power”) techniques. The former resembles what it is depicted in Figure 3, whereas the latter involves marked and prolonged hip joint piking as the gymnast passes through the handstand position (Figure 4). Optimization solutions led to the conclusion that although the “traditional” technique may generate slightly more angular momentum, the “scooped”
may require less energy and, therefore, may be preferable, especially at the
end of routines when gymnasts are more fatigued. In addition, the scooped
technique may be advantageous by providing a wider release window and,
therefore, greater margin of error than the traditional swing (Hiley and
Yeadon, 2003) and by increasing the gymnast-bar system total energy
during the first (downswing) phase of the giant swing (Arampatzis and
Brüggemann, 1999).

Insert Figure 4 about here

3. **Special considerations for uneven bars.** Until recently, female gymnasts
had to consider additional limitations imposed by the space restrictions
imposed by the width of the bars. These restrictions, however, are less
constraining today except for some of the tallest gymnasts, because the
distance between the rails has been considerably increased from previous
settings. An additional consideration for uneven bars reflects the greater rail
circumference and therefore different “gripping” as compared to the high bar.
The larger the diameter of the rail or bar the less the gymnast can grasp the
total circumference of the rail or bar. As the circumference gets larger the
potential for slipping from the rail or bar increases. Moreover, gymnastics
swinging grips have been designed to ensure that the hands can maintain a
relatively high level of friction between the rail or bar and the gymnast’s
hand(s). As hand grip positions become more complicated they usually become more difficult due to a decreased area of hand and rail or bar contact.

4. **Bar elasticity.** The elastic nature of gymnastic bars allows the possibility of storing/recovering energy by employing an appropriate technique. As research has shown, however, this may not always be attainable since in many cases, gymnasts may release the bar when it rebounds, which not only does not add energy to the gymnast, but may have a negative effect on gymnastic technique. Gymnasts can use the rail or bar elasticity to determine the proper timing of a skill based on the tension felt on their hands as the bar bends and recoils. Gymnasts also use the recoil of the rail or bar as an essential aspect of skill performance such as in the Tkatchev or reverse Hecht which relies on the second of two rail/bar recoils to help pull the gymnast high over the rail or bar and places the gymnast in a position to regrasp the rail or bar.

**Ability to land:** The variables dictating the success or failure of landing in a typical backward translating backward rotating landing (Figure 5) are: (1) angle of the gymnast's body from the horizontal ($\theta$), (2) ground reaction force ($F$), (3) angular momentum of the gymnast's body ($L$), (4) linear momentum of the
gymnast’s Center of Mass (M), and (5) the distance of the CG from the vertical axis (d).

Data from the 2000 Olympics indicate that the majority of both male and female gymnasts failed to “stick” the landing in vaulting (McNitt-Gray, Costa et al., 2001; McNitt-Gray, Requejo et al., 2001). The same data indicates that more gymnasts over rotate than under rotate and that female gymnasts fair worse. Lastly, these data revealed that, in both genders, forward translating/forward rotating vaults are the most difficult to control. Cumulative data from more apparatuses reveals an overall success “stuck” landing rate of approximately 50 percent for elite gymnasts (Sands et al., 2003).

A discussion of some of the reasons why it is difficult to consistently “stick” landings has been presented in a previous paper (Prassas, 1999b) and is adapted for a handspring double layout somersault landing, a very difficult skill (Figure 5). A skill such as this requires that the gymnast perform a takeoff with a large amount of angular momentum. Due to the momentum conservation principle, the gymnast’s angular momentum at touchdown (L, Figure 5) will be the same as at takeoff. What reduces the angular momentum to zero after touchdown is the angular impulse from the floor. Angular impulse (the physical variable that changes angular momentum) is the product of average torque and the time the
torque acts. Torque, in turn, is the product of force and its moment arm, the
perpendicular distance from the axis of rotation:

$$\Delta L = \bar{r} \cdot t$$

It is an extremely difficult task to first generate and then withstand the undoubtedly
extremely high ground reaction forces encountered at impact for difficult skills as
the one discussed previously and to time the touchdown with an “optimum"
horizontal CM-feet distance (d, Figure 5). If that distance is too small, the body will
most likely still be rotating backward when the CM passes over the feet and, as a
result, the gymnast will have to take one or more backward steps in order to
maintain balance or the gymnast may even fall. On the other hand, if the gymnast
lands with too long a horizontal CM-feet distance, the somersaulting angular
momentum may be reduced to zero when the CM is still in front of the feet. To
avoid falling forward, the gymnast must take one or more forward steps to maintain
balance, or place his/her hands on the floor. It should be mentioned that before
the gymnast takes these step(s), he/she might attempt other corrective actions—
such as rotating the arms and/or (excessively) flexing the hips and/or knees. The
first action is based on the “transfer” of angular momentum principle, which, if
successfully applied, may “transfer” enough angular momentum from the
gymnast’s body to the upper extremities thus enabling the gymnast to avoid the
undesirable effects described previously. The second action, flexing the hips
and/or knees, is based on the gymnast’s attempt to increase the landing time and,
thus, to decrease the average ground reaction force that brings the body to rest.
The same principles apply to the forward translating/forward rotating landings, such as front somersaults in floor exercises and front handspring/front somersault vaults. The lower landing success rate for these type of vaults reported by McNitt-Gray et al., (2001) may be attributed to the gymnasts reduced ability to get kinesthetic feedback that results in spatial orientation, “spot” the mat (i.e., see the mat as early in the landing phase as possible), and make necessary adjustments. In addition, in the landing from backward somersaults, gymnasts normally flex the hip at landing. This will move the body CM toward the landing foot. In order to slow down the rotation, the mat reaction force vector has to pass the CM posteriorly and the moment arm of the mat reaction force about the hip becomes short. Therefore one can effectively resist against the mat reaction force using the leg muscles (hip and knee extensors) through pushing the mat. In the forward landing, however, the moment arm of the mat reaction force about the hip becomes relatively long and the torque will be larger than in the backward landing. The resistance torque must be generated by the hip and knee extensors. In other words, for the same muscular efforts, it is more difficult to resist against the mat reaction force in the forward landing.

It should be noted that difficulties in sticking landings are multiplied when rotation(s) about the longitudinal axis are added to somersaulting. These difficulties are linked to the associated actions necessary to remove the twisting before landing and exacerbated when the twisting has to be stopped after touchdown. Finally, the magnitude of skill and force level required in combinations
of skills with reversal of rotation—such as forward somersault(s) following backward ones—is undoubtedly much greater since the angular impulse must reduce and then reverse the gymnast’s rotational direction. The complexity and multiple strategies undertaken by gymnasts during landings have been illuminated in a series of studies by McNitt-Gray et al. (1993; 1994; 2001; 2004).

**Balance:** Gymnasts perform static skills—such as handstands and scales—moving to a still position with a slow, controlled motion, or after swings or other movements. Thus, gymnasts require possession of both static and dynamic balance. Since dynamic balance requires gymnasts to reduce some level of angular momentum to zero, the previous discussion on landings may be adapted and applied to dynamic balance. Dynamic balance in another form—when a gymnast is already in motion, but with the line of gravity outside the base of support—is also a factor that gymnasts must consider when executing skills that do not end in still positions.

Gymnastics constantly moves in the direction of fewer degrees of freedom when skills are performed, particularly in terms of balance skills. For example, as the gymnast learns to perform a handstand, initial attempts involve multi-joint strategies in order to attain and maintain balance. As the gymnast progresses, the number of joints and the extremes to which the joints move decreases. However, when the gymnast experiences trouble in maintaining balance, more joints become involved. This was shown by Kerwin and Trewartha (2001) in a study of anterior-
posterior balance adjustments in a handstand. Although the wrist torques were
dominant, in less successful balance attempts the shoulders and hips played a
larger role.

Research in Gymnastics

Tumbling/Floor Exercises
The great majority of floor exercise routines for both men and women consist of
jumping/rotating elements interconnected by simpler transitional skills.
Subsequently, most research in floor exercises examines the takeoff and landing
characteristics of various types of somersaults, mostly backward. To that extent,
Hwang et al., (1990) investigated takeoff mechanics of three different types of
backward somersaults performed at the 1988 Seoul Olympic Games, including the
contribution of different body parts to the total angular momentum. As expected,
the required angular momentum increased from the double-tucked to double-
tucked-with-a-twist to the double-layout. In all cases, the legs' contribution to the
total angular momentum was dominant. Similar takeoff mechanics were found by
Kerwin et al., (1998) who investigated the production of angular momentum in
double backward somersaults performed during the 1996 Olympics. Angular
momentum and center of mass (CM) kinematics of single and double backward
somersaults were investigated by Brüggemann (1983). Knoll (1993) examined the
same parameters when studying implications for round-off and flic-flac techniques,
concluding that maximum height and takeoff angular momentum must be
optimized.

Takeoff and landing characteristics of double back somersaults on the floor,
performed at the 1994 World gymnastics championships, were studied by
Geiblinger et al., (1995a; b) and the kinematic results presented are in agreement
with previous literature. Burgers and Noffal (2002) showed that advanced
gymnasts exhibited greater vertical and lower horizontal takeoff velocities and
shorter takeoff contact times during back tucked somersaults than beginners. In
addition, they found that during takeoff, horizontal velocity was invariably
decreasing as vertical velocity was increasing. The study of different types of back
somersaults from simple (single tucked) to very difficult (double layout) by Hraski
(2002), showed inverse/direct relationships between angular momentum in flight
and vertical/horizontal takeoff velocities, respectively.

Yeadon and Kerwin (1999) indicated that, although the countermovement,
or hula hoop technique, can generate twisting in tumbling, gymnasts utilize mostly
tilting to twist. Furthermore, it was shown that the majority of tilt is produced by
aerial vs. contact techniques. In a subject-specific tumbling optimization, Yeadon
and King (2002) showed that somersaulting height can be improved by varying the
timing of the torque generators. King and Yeadon (2003; 2004a; b) used
optimization techniques to study the effect of approach and takeoff perturbations
and the corresponding coping mechanisms of the gymnasts as well as the effect of
approach technique on tumbling performance including maximization of somersault rotation.

*Forward somersaults* have received less attention. The *Russian* arm swing technique, favored by the majority of gymnasts in the past, was studied by Knight *et al.*, (1978) who concentrated mainly on the action of the arms. Ground reaction forces—also for the *Russian* type of *somersaults*—were examined by Miller and Nissinen (1987) to investigate force characteristics in relation to performance. Lastly, Brochado and Brochado (2002) examined takeoff kinematic differences between front somersaults on floor and on different trampolines.

In summary, there is a wealth of information and good understanding of somersaults' takeoff requirements. Competitive landings, however, have not been studied as much and, consequently, are not as well understood, although McNitt-Gray *et al.* (1993; 1994; 2001) have studied landing mechanics and some of the findings can be applied to floor somersault landings as well as dismount landings from other apparatuses. In addition, there is limited information on the extremely high loads placed on the muscle/tendon system during the short contact time in both takeoffs and landings. As discussed previously, these loads are accentuated when combinations such as backward-somersaults immediately followed by forward-somersaults are performed. Recently, a prediction model attempted to identify anthropometric and physical prerequisites for tumbling/vaulting ability (Bradshaw and Le Rossignol, 2004). A summary of research findings for tumbling/floor exercises is presented in Table 1.
Vaulting

Vaulting is the only apparatus involving a single movement and, for this reason, vaulting is the most researched and best understood apparatus. While the Yurchenko and some other vaults have been investigated (Brüggemann, 1984; Kwon et al., 1990; Takei et al., 2000; Koh et al., 2001; Koh et al., 2003; Bohne et al., 2000; Sprigings and Yeadon. M., 1997; Dillman et al., 1985), handspring-type of vaults have received more attention. To that extent, studies by Bajin (1979), Dainis (1979;1981), Takei (1989; 1990; 1991a; b; 1992; Takei et al., 1996; Takei, 1998), Takei and Kim (1992), Lee (1998), Krug et al., (1998), and Takei et al., (2003) have examined springboard parameters, parameters while in contact with the table, landing parameters, correlations between mechanical variables and the scores given to the vaults by qualified judges, and/or correlations between high and low scored vaults. As a result, it is generally accepted that, in vaulting, running approach horizontal velocity and takeoff springboard linear and angular parameters may be more important than parameters during table contact. However, the advent of the Yurchenko vault where the need to strike the takeoff board accurately is accentuated due to the complexity and “blindness” of the round off entry may have reduced the importance of a very fast and longer run at least as compared to handspring-type of vaults (Sands, 2000; Sands and McNeal, 2002). Moreover,
within each family of vaults, greater running speed is still required to execute more
difficult vaults (Bradshaw, 2004) and earlier work has shown that it is very difficult
to compensate for errors made during run up and takeoff while in contact with the
table. It is also generally accepted that the initial (takeoff) angular momentum is
invariably reduced during contact with the table, with a portion in a sense utilized to
increase vertical velocity, and that in most successful vaults, angular momentum is
reduced the least. A model developed by Dainis (1981) for the airborne and table-
support phases of handspring vaulting established some of the aforementioned
relationships, clearly showing that springboard takeoff velocity and distance from
the table to be the principle variables affecting the outcome of the vault.

Two studies by McNitt-Gray, et al., (2001) revealed that more than 50% of
both male and female gymnasts failed to stick the landing during the 2000 Olympic
Games; that the females faired worst, and that in both genders, forward
translating/forward rotating vaults were the most difficult to control. Finally,
although it is widely understood that the majority of the energy required in vaulting
is generated during the preceding short sprint, this phase has received little
attention (Krug et al., 1998). A recent study suggests that, contrary to common
practice where most gymnasts precisely measure the exact distance from where
they begin their approach, gymnasts should be encouraged—and practice—to rely
on visual cues to “hit” the springboard “on stride” with minimal loss of running
speed (Bradshaw, 2004). A summary of available information for vaulting is
presented in Table 2.
Horizontal Bar and Uneven Bars

Research on the horizontal bar has focused on dismount and/or flight elements and the mechanics of associated giant swings. Some transitional techniques and an ever-increasing number of release-regrasp skills have also been investigated. George (1970) offered some of the first descriptive data for four different types of giant swings. Additional kinematic, kinetic and EMG data for giant swings have been reported by a number of investigators (Boone, 1977a; Yamashita et al., 1979; Cheetham, 1984; Prassas and Kelley, 1985; Okamoto et al., 1989) and the transition to the inverted giant swing (the "stoop-in") was studied by Prassas et al., (1988). In addition, the energetics of high bar giants has been studied by Okamoto et al., (1989).

Yeadon et al., (1990), Kerwin et al., (1990), and Yeadon (1997) utilized data obtained at the 1988 Seoul Olympic Games to determine the contributions of contact and aerial techniques in high bar dismounts employing twisting, and to examine the necessary modifications in body configurations and angular momentum needed in multiple somersault dismounts. Using the tilt angle as a measure of twisting potential, these investigators concluded that: a) the major source of twisting was aerial asymmetrical arm and hip movement, and b) in dismounts with multiple twists, twisting technique varied according to body
configuration—layout versus another body shape—and location of twisting within the (first or second) somersault. It was also found that execution errors such as thigh abduction (i.e., legs apart) in triple somersault dismounts could be eliminated with only small increases in angular momentum. Simulated data, however, revealed that removal of arching during double layout dismounts would have resulted in under-rotation. Comparative double layout and triple tucked somersault dismount data revealed that the former requires greater angular momentum whereas vertical velocity/flight time/maximum height is more important in the latter dismount. Similar comparative results between double layout and triple tucked somersault dismounts were also found by Park and Prassas (1995). Takei et al., (1992) found significant correlations between vertical release velocity, height above the bar and total time in the air in successfully performed double somersault dismounts. Although Kerwin et al., (1990) and Okamoto et al., (1989) reported that the CM at release was above bar level in some gymnasts, a study by Kerwin et al., (1993) indicated that this may be due to methodological errors. Additionally, it was found that tangential motion was the major contributor to horizontal release velocity with radial and bar contributions for some gymnasts.

In order to establish profiles for the different dismounts and release-regrasp skills and to identify differences between the techniques studied, Brüggemann et al., (1994) studied the mechanics of seventy dismounts and release-regrasp skills performed at the 1992 Barcelona Olympic Games. The skills were divided into 10 groups and, among them, three groups were found to be significantly different in
terms of maximum values and timing of a variety of kinematic and kinetic variables. *Release-regrasp* elements have also been studied by Prassas and Terauds (1986), Prassas (1990), Gervais and Talley (1993), Brüggemann *et al.,* (1994) and Cuk (1995). Holvoet *et al.,* (2002) indicated that a major problem with the execution of the *Tkatchev* on the high bar is early release. In addition, the study indicated that the timing of hip/shoulder motion in flight is critical to the skill as is the stabilization of the upper extremities in flight.

Arampatzis and Brüggemann (2001) studied the gymnast-bar energy exchange during the giant preceding a *Tkatchev* and indicated the importance of muscular work through shoulder and hip action during the later phases of the swing up to release. The same authors indicated that the nature of the bar-gymnast energy exchange varies depending on both the apparatus or gender and the flight element or dismount (Arampatzis and Brüggemann, 1999). The largest energy lost was found during the second phase of forward giants performed on the uneven bars. Furthermore, Arampatzis and Brüggemann (1998) showed that delayed and initially slow and even reduction in hip and shoulder joint angles during the giant preceding dismounts can increase total body energy by 15%, release vertical velocity by 10%, and angular momentum by up to 35%.

A comparative study of the horizontal bar kip performed by skilled and unskilled gymnasts demonstrated the importance of timing of joint action, especially hip flexion, which must be performed later than when it is usually performed by novice gymnasts (Yamada *et al.,* 2002). Some of the horizontal bar
In general, similarities between the mechanics of the uneven bars and high bar dismounts and flight elements' giant swings result in similarities in some release conditions. However, differences in the “beat” action (i.e., “tap” or sudden transition from an arched body position to a piked or flexed body position) through the bottom of the swing, differences in the physical characteristics, design and construction of the apparatuses and anthropometric differences between male and female gymnasts may explain some of the kinematic and kinetic differences between the two apparatuses. Those differences, particularly a delayed execution of the beat action (Knoll, 2002), may be the source of the large energy losses found by Arampatzis and Brüggemann (1999) during the second phase of forward giants preceding dismounts and flight elements. An optimization study by Sheets and Hubbard (2004) revealed that stronger gymnasts may maximize the number of dismount revolutions in high bar/uneven bars regardless of the inertial properties of the gymnast in part by including atypical and larger range of motion of the CM away from the rail during the first part of the downswing of the last giant swing. A summary of biomechanical research on horizontal bar and uneven bars is presented in Table 3.
Rings and Parallel Bars

The type and difficulty of skills on still rings and parallel bars have rapidly changed over the last decade with swinging skills currently comprising a major part of gymnasts' routines. Research, however, has not progressed equally. With regard to the still rings, Nissinen and Brüggemann (cited by Brüggemann, 1987) first presented kinematic and kinetic profiles of straight arms giant swings contradicting coaching opinions of the times. Optimization solutions for backward giant swings by Sprigings, et al. (1998; 2000), and Yeadon and Brewin (2003) indicated that: a) removal of swing during hold parts on the still rings is best achieved if the downswing is initiated when the "swinging handstand has reached the bottom of the swing-arch"; b) the hip flexors' primary role is to prevent hip joint hyperextension, whereas the primary source of energy is the shoulder musculature, and c) changes in body configuration must be timed to occur within 15 milliseconds of the optimal timing to avoid residual swing in the handstand. Geiblinger et al., (1995c) reported kinematics of a case study of the "stretched double fledge backward to forward swing in hang" known otherwise as the "O'Neil". Yeadon (1994) studied twisting techniques used in dismounts at the 1992 Olympic Games, concluding that the majority of gymnasts use asymmetrical arm action to initiate twists.
Research on the parallel bars is also not extensive. The feldge (or peach basket) has been studied by Boone (1977b) and Takei et al., (1995) who compared the (traditional) inner and (newer) outer grip techniques in the feldge to handstand mount. It was concluded that the outer grip has advantages over the inner by elevating the body’s CG more at regrasp. Liu and Liu (1989) presented a case study on swings in the extended hang (cited by Brüggemann, 1994). A quasi-static movement, the press handstand, was studied by Prassas et al., (1986), and Prassas (1988; 1991). Prassas also reported on the techniques of two basic skills, the back toss (1994) and the backward somersault dismount (1995b). The dynamics of both skills have been investigated by Prassas and Papadopoulos (2001). Differences in vertical and horizontal forces during the upward, pushoff phase were found and these differences were related to the greater height attained in the back toss and the need for different horizontal flight displacements. A comparative study of double back salto dismounts by Gervais and Dunn (2003) revealed that better dismounts were characterized by greater vertical velocity at release, but less angular momentum than poor ones. A case study of the double back somersault dismount was presented by Manoni, et al., (1993a) who also reported on different types of forward somersaults (1993b). As with Manoni et al., (1993b), Kolar, et al., (2003) also concluded that, in performing (any) forward saltos on the parallel bars, the actions during the preparatory swings are most critical. Table 4 summarizes the research-based information on the rings and the parallel bars.
As mentioned previously, women’s gymnastics research is limited. Among the few studies conducted, Brown, et al., (1995) investigated ground reaction forces in two relatively simple dismounts from the balance beam, which were found to be over 10 times body weight. In a follow-up study, for more difficult somersault dismounts, the forces were up to 13 times body weight (Brown et al., 1996). As a result, they suggested that, at least in practice and possibly in competition, gymnasts should be allowed to roll-out of various dismounts—a suggestion highly unlikely to be adapted by gymnastics’ governing bodies. Knoll (1996) found that gymnasts employ the same biomechanical mechanisms in the performance of acrobatic tumbling exercises on floor and balance beam, i.e. trade-off between takeoff angular momentum and takeoff linear velocities.

The pommel horse is considered one of the most difficult apparatuses and biomechanical research could be of extra value to practitioners. However, research is limited to a case study comparing the Thomas flair spindle and the Magyar spindle (Cuk and Karascony, 1995). It was concluded that, although the (kinematic) results suggested that the former may be more difficult, the fact that gymnasts perform the Magyar spindle less frequently suggests that it is more
difficult—“they (the gymnasts) know best how difficult an element is”. A summary of miscellaneous research in gymnastics is presented in Table 5.

Insert Table 5 about here

**Future Biomechanical Research in Gymnastics**

Gymnastics provides almost limitless possibilities for the study of human motion, but this fact also makes gymnastics extremely frustrating because skill selection for study can be daunting. The nature and complexity of human movement necessitates the undertaking of a large number of studies to understand even one activity or skill. For example, a great number of studies have been devoted exclusively to locomotion. Consequently, gymnastics, with its hundreds of skills, would require an untold number of studies before it is completely “understood”.

Attempts at gymnastics taxonomies have largely failed due to the enormous number and complexity of skills (Brüggemann, 1994). With the acknowledgement that every study makes a contribution, sound experimental protocol would make every contribution greater. Here are some factors to be considered:

As indicated previously (Prassas, 1999), biomechanics is uniquely positioned to assist with regard to:

- understanding of existing techniques,
- new skill development,
• increase in safety,
• equipment design and/or modification, and
• athlete-apparatus interaction

Legitimate questions such as:
• what does it take to do a quadruple somersault?
• how many twists are possible?
• how flexible should the bar(s) be? or
• how springy should a floor or a spring board be?

are those to which biomechanics may assist in finding proper answers. Towards that purpose, descriptive studies of gymnastics skills should continue to be undertaken—description, after all, is the first step in understanding motion and is needed as realistic input to skill simulations. Scientific efforts, however, that attempt to develop principles applicable to an ever larger number of gymnastic techniques would be invaluable. The ultimate success would be the development of a set of principles applicable to all new and existing skills that would have the ability to "explain the sport of gymnastics".

Future gymnastics research will need to consider some important data collection-related issues:

1. **2-D or 3-D**: should be primarily determined by the nature of the skill to be analyzed. Since most gymnastic skills—or a phase within most skills—involve some type of complex rotations, the norm should be 3-D. In the case
of 2-D analysis, calibration frame-based camera calibration method such as the 2-D DLT (Kwon and Fiaud, 2002; Brewin and Kerwin, 2003) provides several advantages over the conventional scaling factor-based method: 1) the camera does not have to be set perpendicular to the plane of motion, and 2) multiple cameras can be used to improve the analysis accuracy and/or to increase the relative image size. The calibration frame-based method is more suitable for the competition setting since it has fewer restrictions in terms of the camera placement. In general (2-D/3-D), the size of the calibration frame is important. The control volume/area defined by the calibration frame must be large enough to embrace the volume/area of motion. Use of the apparatuses of known size (Yeadon, 1994) or use of range poles (Kwon, 1996) can easily increase the control volume.

2. **Image size**: the size of the gymnast in the image should not be so small that recognition/digitizing of individual joints/points is difficult and deviates substantially from frame to frame. Re-digitizing and running reliability tests would give an indication of the ability to consistently digitize a given joint/point. However, the size of the subject in the view can be increased substantially by utilization of panning software or by adding more cameras. With a calibration frame-based camera calibration method such as DLT, it is easy to add more cameras. Adding more cameras also increases the chance to observe a point/joint from at least two camera views (in 3-D) and
reduces the need for guesswork in the digitizing process. The more guesswork is required, the less accurate the analysis will be.

3. **Frame rate**: for practical reasons, 50 or 60 Hz (with de-interlacing or field separation) has been the norm in the majority of previous research. Although these rates may be marginally appropriate for the analysis of some gymnastics skills, other skills require higher rates. This is particularly true for studies involving specific phases of an overall skill—such as takeoffs and landings and release/regrasp skills where body configuration changes abruptly. Results of skills/critical phases lasting fractions of a second cannot be valid when the time interval between data points is as large as 1/50th of a second. Although improving, the cost of the high-speed video cameras still remains as the main obstacle. The gymnastics investigator is often constrained by lighting due to indoor venues and poorly illuminated gymnasiums. Shutter speeds are usually a compromise between obtaining a higher frame rate and maintaining a visible subject. Fortunately, reflective markers often reduce the need for high intensity lights, but reflective markers also mean some intrusion on the gymnast which is not always practical or possible.

Future research will also need to consider some important analysis-related issues:
1. **Spectator perspective vs. gymnast perspective**: the conventional approach has been the spectator (global) perspective. Describing biomechanical (kinematic and kinetic) quantities in the spectator perspective often has limitations in terms of the usefulness of the research findings since the findings are in most cases the effects of posture control by the gymnast and the gymnast-apparatus interaction. Employing the gymnast perspective in the analysis is important in this sense. Quantifying the joint motions and assessing the muscular efforts of the gymnasts is essential to understand the biomechanics of gymnastics and to improve the performance of athletes. For example, at the U.S. Olympic Training Center male gymnasts are currently experimenting with the use of video goggles for learning positions that they cannot normally see during their performance. This approach provides the gymnast with a view of his position as judges or spectators would see him. This type of feedback has already shown promising results.

2. **Descriptive vs. explanatory**: another main problem in gymnastics research has been their descriptive nature. Selected mechanical quantities (mostly kinematic) at events (meaningful instants) or phases have been used in correlation analyses or comparisons among subject groups of different skill levels. Although the inter-correlations among different biomechanical quantities of the events and phases and the inter-group differences may certainly provide important insights into the biomechanics of
gymnastics, they may not shed light on the cause-and-effect relationships existing in the gymnastic performances. It is necessary to shift the focus of research to the posture control by the gymnast and the gymnast-apparatus interaction. The required muscular efforts on the part of the gymnasts for successful and accurate postural control and interaction with the apparatuses must be studied in depth. In simple symmetric movements, the gymnast-apparatus interaction can be analyzed easily based on the acceleration of the center of mass of the body. In complex movements, efforts must be directed toward the instrumentation of the apparatuses to directly measure the gymnast-apparatus interaction.

3. **Forest vs. individual trees**: the majority of the previous gymnastics research has been totalitarian, perhaps due to their descriptive nature and focus on the inter-relationship among selected biomechanical quantities, looking at the entire movement segment. This approach provides an advantage in terms of seeing the big picture, the inter-relationships among different phases of the movement segment. However, in-depth understandings of the biomechanics of gymnastics leading to attempts of performance enhancement require more than an obscure big picture. For example, it has been known through research that springboard contact is one of the most important phases in vaulting. The springboard phase variables show significant correlations to the performance outcome. In
theory, however, the most important phase of the vaulting must be the table contact phase because the initial conditions of the post flight such as the vertical velocity of the body center of mass and the total angular momentum are finalized during this phase. Superficial analysis of the table contact phase reveals that gymnasts generally lose angular momentum in this phase but better performers tend to lose less angular momentum and develop more vertical velocity (or lose less). This can be studied in depth by looking at the change in the magnitude and direction of the force acting on the gymnast’s hands from the vaulting table (the table-reaction force). The direction and magnitude of the table reaction force must be a function of hand position on the table, orientation of the body, and linear/angular velocity of the gymnast’s body. Highlighting the gymnast-table interaction during the table contact phase of vaulting may allow us to understand why certain table contact conditions (at the end of the pre-flight) are more favorable over others and the findings may be generalizable. Since the table contact conditions, such as the hand position, body orientation, and linear/angular velocities of the body, are the direct outcome of the springboard and pre-flight phases, the desired springboard and pre-flight movements may be suggested. This process is analogous to putting puzzle pieces together. A big picture with clear details of the pieces must be the desired product of the future research efforts.
4. **Simulation and optimization**: with the improvement in computing power and advancement in knowledge, it is getting relatively easier to perform simulation and optimization studies in gymnastics (Dapena, 1981; Yeadon et al., 1990; Koh et al., 2001; Koh and Jennings, 2002; Kwon, 2002; King and Yeadon, 2003; 2004a; b; Sheets and Hubbard, 2004). Simulations will allow investigators to better understand the cause-and-effect relationships among the biomechanical factors through systematic manipulations of the key performance factors. The quality of the outcome of the simulations depends on the accuracy of the input data and the complexity of the model employed. Optimization studies will allow us to come up with optimized solutions based on the physical characteristics of the gymnast and the practical and biomechanical constraints of the movements. The quality of optimized solutions depends on the accuracy of the input data, the complexity of the model, and the thoroughness of the physical constraints. One important advantage of simulation and optimization is that these approaches intrinsically use the gymnast’s perspective rather than the spectator’s perspective. Simulation and optimization requires a lot of time and effort as well as in-depth knowledge of the procedures and specialized software.

5. **Statistical analysis issues**: the ratio between sample sizes to experimental variables to be analyzed is typically dictated by statistical rules.
This does not preclude the study of unique/difficult skills where sample size may be small, or even confined to a single subject. This should be realized, however, and (possibly) indicated as “case studies”. Another more prevailing issue is that although descriptive statistics and statistical inferences are important in terms of generalization of the research findings, one should not compromise the research problems and rationale for statistical convenience. For instance, looking at the correlations among selected biomechanical quantities (of events and phases) and performing group comparisons among subject groups of different skill levels are statistically more convenient but these approaches may not effectively address the continuous nature of the gymnastic movement segments under investigation. Besides, it is normally difficult in biomechanical research to meet the normal distribution assumption upon which most statistical models are based. Therefore, blind applications of statistical rules without considering the nature of the movement under investigation must be avoided.

6. **Development and sharing of research tools**: interactive and easy-to-use monitoring and simulation/optimization software packages would be valuable tools for both the researchers and practitioners (coaches and athletes) alike. A substantial amount of effort should go to the development and sharing of easy-to-use yet comprehensive software packages. The
software should permit individualized data input, as research has shown that results are sensitive to the input parameters and, therefore, should be individualized (Kwon, 2001; 2002).

7. **Collaboration with coaches and other investigators.** At least in the U.S.A there has been a growing tendency to abandon sport science research and turn to broadly defined “exercise” and public health issues because the funding for sport science is practically nonexistent (Stone et al., 2004). Sport science research in gymnastics has suffered due to these issues and to constantly changing skill performances and the sheer number of skills to be analyzed. Moreover, gymnastics research has also suffered for a lack of collaborative efforts between coaches and scientists from different disciplines. Rarely do gymnasts’ performance problems lie solely in one academic research discipline. A team approach involving coaches, scientists from various specialties, and athletes is clearly a more modern model for the conduct of gymnastics-related research.

**Summary and Conclusions**

The body of research on gymnastics is substantial and growing. Most, however, is still skill oriented with few attempts for generalization. As a result, our
understanding of the principles and bases of the sport is limited with gaps in knowledge regarding technique attributes that can permeate the sport. For that reason, this review commenced with an attempt to identify important performance variables contributing to successful performance. It is suggested that, in the future, scientists find a way to communicate a greater portion of the existing and new information to practitioners—the coaches and athletes. This information should be presented to the practitioners in a meaningful and understandable form (Prassas, 1999). Interactive and easy-to-use simulation/optimization software would be a valuable tool for coaches and athletes. It should be stressed, however, that this software should permit individualized data input, as research has shown that results are sensitive to the input parameters and, as pointed previously, should be individualized.
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Games: Implications for Improved Gymnast/Mat Interaction.


Prassas, S. (1999b). On dismounts, twists, somersaults, etc. or why is it difficult to do that double back layout somersault?


Table 1
Summary of Gymnastics Research on Floor Exercises

<table>
<thead>
<tr>
<th>Skills</th>
<th>Information on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back somersaults:</td>
<td>• Takeoff horizontal/vertical velocity; takeoff angles;</td>
</tr>
<tr>
<td>Single/double (tucked, piked, layout, layout with twist(s))</td>
<td>linear/angular momenta; segmental contributions to angular momentum;</td>
</tr>
<tr>
<td></td>
<td>• Timing/duration of takeoff; joint/body angles during landing;</td>
</tr>
<tr>
<td></td>
<td>• Optimization</td>
</tr>
<tr>
<td>Front somersaults:</td>
<td>• Ground reaction forces; arm motion; joint angles/takeoff timing</td>
</tr>
<tr>
<td>Tumbling ability</td>
<td>• Predictors (of high tumbling ability)</td>
</tr>
</tbody>
</table>
Table 2
Summary of Gymnastics Research in Vaulting

<table>
<thead>
<tr>
<th>Skills</th>
<th>Information on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handsprings type of vaults</td>
<td>• Running/springboard takeoff mechanics.</td>
</tr>
<tr>
<td></td>
<td>• Postflight characteristics.</td>
</tr>
<tr>
<td></td>
<td>• Horse contact mechanics.</td>
</tr>
<tr>
<td></td>
<td>• Postflight and landing characteristics.</td>
</tr>
<tr>
<td></td>
<td>• Vaulting mechanics/judges scores correlation</td>
</tr>
<tr>
<td>Yurchenko vaults</td>
<td>• Springboard takeoff mechanics.</td>
</tr>
<tr>
<td></td>
<td>• Postflight characteristics.</td>
</tr>
<tr>
<td></td>
<td>• Horse contact mechanics.</td>
</tr>
<tr>
<td></td>
<td>• Postflight and landing characteristics.</td>
</tr>
<tr>
<td>Hecht vault</td>
<td>• Springboard kinetics/kinematics</td>
</tr>
<tr>
<td></td>
<td>• Horse kinetics/kinematics</td>
</tr>
<tr>
<td></td>
<td>• Pre-postflight kinematics</td>
</tr>
<tr>
<td>Preceding sprint</td>
<td>• Average/maximum speeds for males/females</td>
</tr>
<tr>
<td>Vaulting ability</td>
<td>• Predictors (of vaulting ability)</td>
</tr>
</tbody>
</table>
### Table 3

Summary of Gymnastics Research on Horizontal Bar and Uneven Bars

<table>
<thead>
<tr>
<th>Skills</th>
<th>Information on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giant swings:</td>
<td>• Joint angles; angular momentum; kinetic energy; force on the bar; power; joint torques; timing; EMG activity; optimization</td>
</tr>
<tr>
<td>Overgrip, Undergrip,</td>
<td></td>
</tr>
<tr>
<td>Inverted, Dismount</td>
<td></td>
</tr>
<tr>
<td>Release/regrasp skills:</td>
<td>• At release/regrasp and in-flight: joint angles; radius of gyration; angular momentum; takeoff angle; flight and regrasp descriptors</td>
</tr>
<tr>
<td>Gaylords, Tkatchovs, Gingers, Kovacs, Kolman, Pegan Mariniches</td>
<td></td>
</tr>
<tr>
<td>Dismounts</td>
<td>• Preparatory giant swing requirements: kinetic energy; CM velocity; angular momentum; joint/body angles; optimization</td>
</tr>
<tr>
<td></td>
<td>• Takeoff mechanics: linear velocity; CM position; body configuration; angular momentum; kinetic energy; optimization</td>
</tr>
<tr>
<td>Kip</td>
<td>• Landing mechanics: body configuration; body angle</td>
</tr>
<tr>
<td></td>
<td>• CM trajectory; hip/shoulder joint angular velocity, torque and power</td>
</tr>
</tbody>
</table>
Table 4
Summary of Gymnastics Research on Rings and Parallel Bars

<table>
<thead>
<tr>
<th>Skills</th>
<th>Information on</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parallel Bars</strong></td>
<td></td>
</tr>
<tr>
<td>Back toss</td>
<td>• Takeoff velocity; angular momentum; body</td>
</tr>
<tr>
<td></td>
<td>position/configuration</td>
</tr>
<tr>
<td></td>
<td>• Upswing dynamics</td>
</tr>
<tr>
<td>Feldge mount</td>
<td>• Body configuration; body position; linear/angular velocity</td>
</tr>
<tr>
<td></td>
<td>• Inner/outer grip differences</td>
</tr>
<tr>
<td>Front somersaults</td>
<td>• Linear/angular momentum of push off swing</td>
</tr>
<tr>
<td>Dismounts:</td>
<td>• Takeoff velocity; angular momentum; body</td>
</tr>
<tr>
<td>Layout, double</td>
<td>position/configuration; joint angles and range of motion</td>
</tr>
<tr>
<td></td>
<td>• Upswing dynamics; maximum (flight) height</td>
</tr>
<tr>
<td></td>
<td>• Landing joint angles</td>
</tr>
<tr>
<td><strong>Rings</strong></td>
<td></td>
</tr>
<tr>
<td>(Giant) swings</td>
<td>• Reaction forces; body configuration; optimization solutions to</td>
</tr>
<tr>
<td></td>
<td>remove residual swing in the handstand</td>
</tr>
<tr>
<td>Dismounts</td>
<td>• Twisting techniques (contact vs. aerial) and segmental</td>
</tr>
<tr>
<td></td>
<td>contributions</td>
</tr>
<tr>
<td>Double salto without</td>
<td>• CM velocity/displacement; timing</td>
</tr>
<tr>
<td>releasing the rings (O’</td>
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<td>Neill)</td>
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</tbody>
</table>
## Table 5
### Miscellaneous Gymnastics Research

<table>
<thead>
<tr>
<th>Skills</th>
<th>Information on</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pommel Horse</strong></td>
<td></td>
</tr>
<tr>
<td>Magyar spindle</td>
<td>• Joint angles; segments’ angular velocities</td>
</tr>
<tr>
<td>Thomas flair spindle</td>
<td>• Same as above</td>
</tr>
<tr>
<td><strong>Balance Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Dismounts</td>
<td>• Ground reaction forces</td>
</tr>
<tr>
<td>Floor/Balance beam</td>
<td>• Angular momentum</td>
</tr>
<tr>
<td>tumbling skills comparisons</td>
<td>• Takeoff velocity</td>
</tr>
</tbody>
</table>
Figure 1. Post flight vaulting score determinants (from Prassas, 2002). The dots connecting linear/angular momentum at horse contact to horizontal energy during sprinting denotes that there are intermediate determinants between.

Figure 2. Double layout somersault with two twists (from Yeadon, 1999).

Figure 3. Giant swing (modified from Kerwin, 1999).

Figure 4. “Scooped” or “Power” giant swing (from Kerwin, 1999).

Figure 5. Landing phase variables (modified from Prassas, 2002).
Figure 1
Figure 2
Figure 4
Figure 5