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Biomechanical Research in Artistic Gymnastics: A Review

SPIROS PRASSAS,[1] YOUNG-HOO KWON[2] and WILLIAM A. SANDS[3]

ABSTRACT

Biomechanical research into artistic gymnastics has grown substantially over the years. However, most research is still skill oriented with few tries at generalization. Consequently, our understanding of the principles and bases of the sport, although improved, is still marginal with gaps in knowledge about technique attributes throughout the sport. For that reason, this review begins with an attempt to identify important 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 each cluster. The last section of the review tries to give some direction to future biomechanical research in gymnastics in issues relating to data collection – two-dimensional or three-dimensional, image size, frame rate – and analysis, such as descriptive or explanatory, simulation and optimization, and statistical issues.

Keywords: biomechanics, gymnastics, research, review.

INTRODUCTION

In contrast to most other sports, which consist of a few activities, or even a single activity, artistic gymnastics includes multiple events; six for men four for women, and, in each event, gymnasts perform routines comprising of many skills. These skills could and, in some cases, have been the subject of several research papers with the end result being quite a large 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 post-flight 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, several

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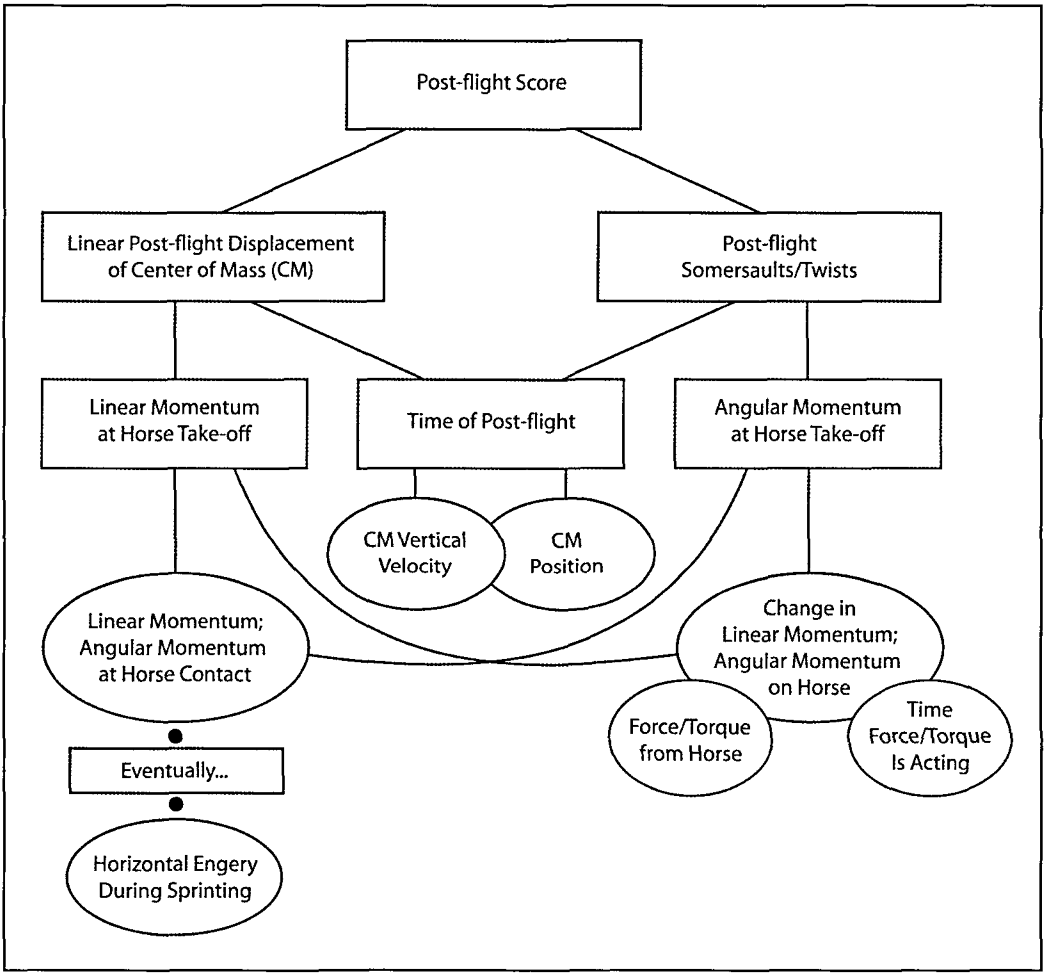

Figure 1 Post flight vaulting score determinants (from Prassas, 2002). The dots connecting linear and angular momentum at horse contact to horizontal energy during sprinting denotes that there are intermediate determinants.

review articles have been published previously (Brüggemann, 1994; Prassas, 1995a; 1999a; Sands *et al.*, 2004). This review paper continues and builds on the previous work by, first, trying to establish 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 would not be constrained to 10 points and competitors would be able to set a world record in gymnastics by a combination of exceptional execution and difficulty. The details of how this new approach might 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 two 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 (Federation International de Gymnastique (FIG), 2002). 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 many variables influence success in the sport, including psychological and physiological factors, biomechanical considerations as reflected in correct or incorrect technique are crucial. With few exceptions, gymnasts must develop the following technique attributes that apply to most skills and apparatuses:

Ability to gain height

One of the most important ways for a gymnast to distinguish his or her performance is by height of flight, for example post-flight 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 or skill is determined by the take-off vertical velocity. In vaulting and tumbling skills, vertical velocity is directly related to the ability of the gymnast to utilize both the horizontal energy generated during the run and 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, of the vertical jumping abilities of the gymnasts. For release and re-grasp skills on both the horizontal bar and the uneven or parallel bars, as well as dismounts from these apparatuses and from the rings, vertical velocity and, therefore, height depends mostly on the ability of the gymnast to partition correctly 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

Most gymnastics skills include some somersaulting, twisting or both. In airborne rotational skills – included in floor exercise, vaulting, uneven or parallel bars, horizontal bars, and still rings dismounts – the gymnast rotates about his or her centre of mass. Of paramount importance in successfully performing rotational skills is the ability of gymnasts to develop or control the somersaulting or twisting angular momentum. Angular momentum is determined by two factors: the moment of inertia, which increases as gymnasts assume a more extended or 'layout' body configuration, and angular velocity, the 'spin' the body or body part possesses. The simplest, and probably the most common, method of creating rotation in gymnastics is an eccentric push of the legs or arms against the supporting surface (here, eccentric means that the direction of the force between the gymnast and surface does not pass through the centre of mass of the gymnast). This force then produces a torque that initiates a turn of the body around its centre of mass that continues once the athlete becomes airborne; this is perhaps the most commonly used mechanism for producing multiple twisting somersaults in gymnastics owing 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 or her fixed feet and thus begin to somersault. If the gymnast skilfully jumps during the period of time for which the feet are fixed, then the gymnast may add enough height and flight time to allow him or her to somersault one or more total revolutions and land back on his or her feet. A simple way to increase the gymnast's somersault rotation is by moving faster horizontally 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 take off 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 take-off 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 various ways, as follows.

Generating 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. 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 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.

Transferring angular momentum 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 or she may over-rotate, quickly spins a body part, usually the upper extremities, in the direction of whole-body rotation. This 'transferring' of angular momentum from the body to the body parts slows down the rotation of the gymnast's body, increasing the possibility of a successful landing.

Increasing or decreasing 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 or twists increases or as the body configuration increases from a tight tuck – with a small moment of inertia – to a full layout, with a 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 take-off angular momentum is not sufficient to complete a predetermined skill, then he or she may, if physically possible, tuck tighter. 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 before landing. Thus, gymnasts usually 'open up' before landing to decrease the rate of spin.

Ability to swing

Gymnasts use swings in various movements including kips and casts. Moreover, gymnasts swing from various body parts – hands, feet with hands, upper arms, and shoulders. Gymnasts swing as a pendulum when swinging from the hands with a straight body, and in more complex ways with multiple pendulums 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 gymnastic performance. Although swings are important in these movements and as links between balance movements on still rings and parallel bars, they become of paramount importance as preparatory manoeuvres for release and 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 and regrasp skills and dismounts.

Factors affecting swing

Three factors affect swinging: the friction between the gymnast's hands and the apparatus, air resistance, and the torque of his or 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 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 2 depicts a giant swing. If the gymnast begins the downswing from a still position (position 1 in Figure 2) and remains rigid throughout, he will 'stall' during the upswing owing to the effect of friction and air resistance. If starting from a moving 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 the moment of inertia on the upswing and, thus, the torque produced by the weight, by decreasing the weight's moment arm – the perpendicular distance from the centre of rotation (the high bar) to the line of action of the weight (see **d**, Figure 2).

Most gymnasts are not concerned with just completing rotations. Their aim

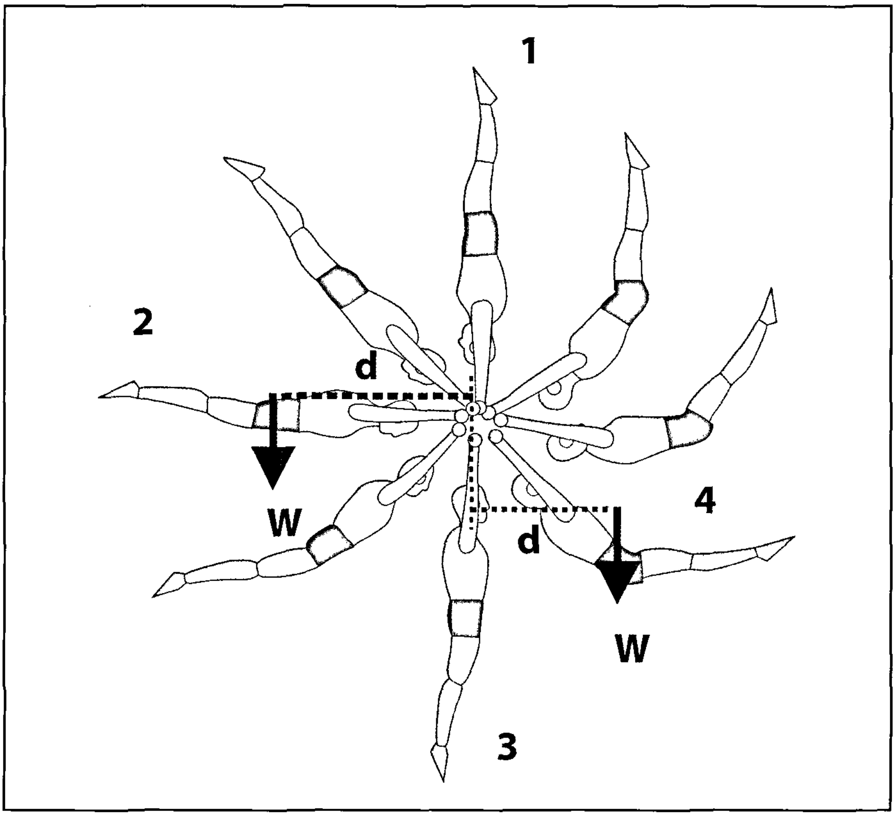

Figure 2 'Traditional' giant swing (modified from Kerwin, 1999).

is to be able to increase or attain the necessary angular momentum for a specified release and regrasp skill or dismount. Depending on the apparatus, gymnasts may use various techniques to achieve this purpose. An obvious technique uses as much 'elongation' as possible or as permitted by the apparatus constraints, such as the low rail of the uneven bars, on the downswing, followed by flexion-extension at the hip and shoulder joints on the upswing. The prescribed downswing action effectively increases angular momentum by increasing the angular impulse of the weight, whereas the shoulder and 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 used by gymnasts to take advantage of the muscle length-tension relationship and the bar or rail elasticity.

Traditional and 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 2, whereas the latter involves marked and prolonged hip joint piking as the gymnast passes through the handstand position (Figure 3). Optimization solutions led to the conclusion that

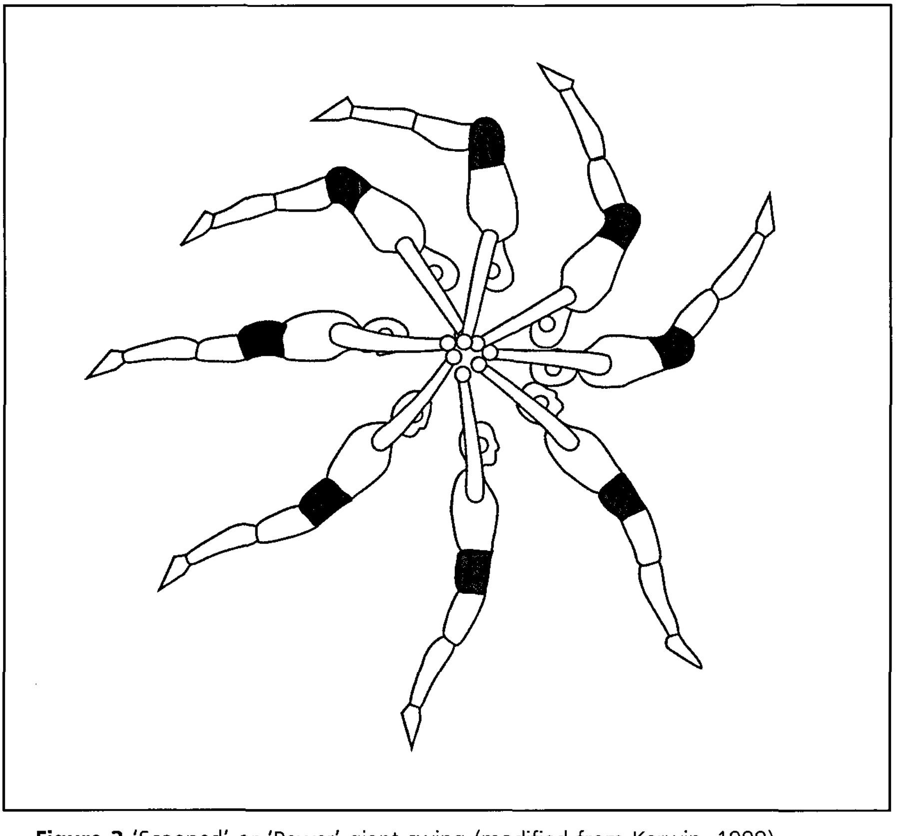

Figure 3 'Scooped' or 'Power' giant swing (modified from Kerwin, 1999).

although the 'traditional' technique may generate slightly more angular momentum, the 'scooped' may require less energy and, therefore, may be preferable, particularly 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 phase – the downswing – of the giant swing (Arampatzis and Brüggemann, 1999).

Special considerations for uneven bars

Until recently, female gymnasts had to consider additional limitations caused 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 frictional force between the rail or bar and the gymnast's hands. As hand grip positions become more complicated, they usually become more difficult because of a decreased area of hand and rail or bar contact.

Bar elasticity

The elasticity of gymnastic bars allows the storage and recovery of energy by using 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 also 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 rely on the second of two rail or bar recoils to help pull the gymnast high over the rail or bar and place 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 4) are: the angle of the gymnast's body from the horizontal (θ), the ground reaction force (**F**), the angular momentum of the gymnast's body (**L**), the linear momentum of the gymnast's centre of mass (**M**), and the distance of the centre of mass from the vertical axis (**d**).

Data from the 2000 Olympics indicate that most male and female gymnasts

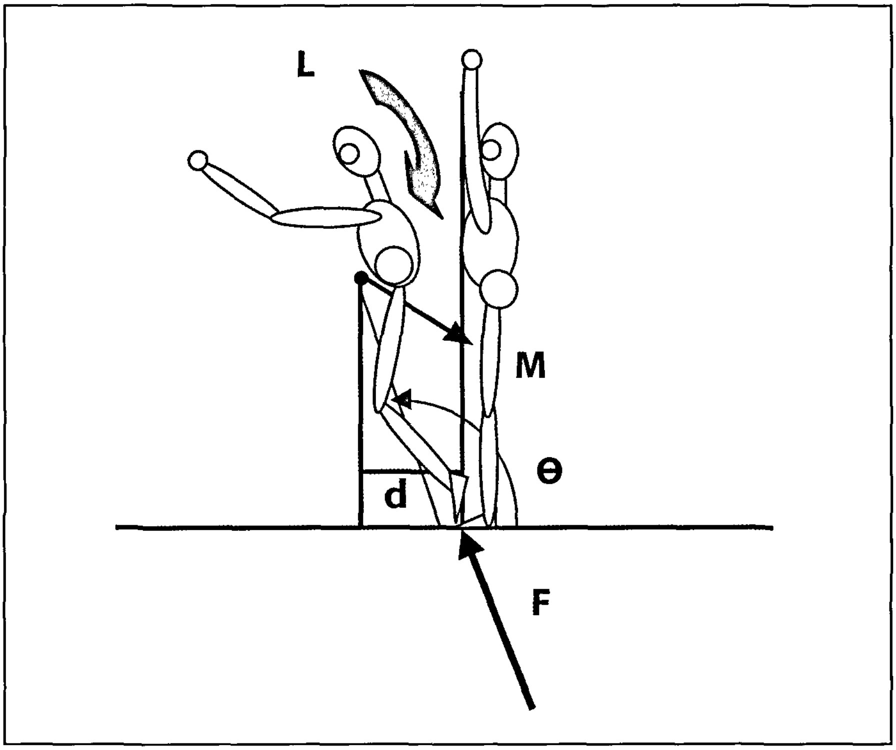

Figure 4 Landing phase variables (modified from Prassas, 2002).

failed to 'stick' the landing in vaulting (McNitt-Gray *et al.*, 2001a; b). The same data indicate that more gymnasts over-rotate than under-rotate and that female gymnasts do worse. Lastly, these data revealed that, for males and females, forward translating and forward rotating vaults are the most difficult to control. Cumulative data from more apparatuses reveal an overall success 'stuck' landing rate of approximately 50% for elite gymnasts (Sands *et al.*, 2004).

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 4). A skill such as this requires that the gymnast performs a take-off with a lot of angular momentum. Owing to the momentum conservation principle, the gymnast's angular momentum at touchdown (**L**, Figure 4) will be the same as at take-off. What reduces the angular momentum to zero after touchdown is the angular impulse from the floor. The angular impulse – the physical variable that changes angular momentum – is the product of average torque (T_{av}) and the time (t) the torque acts: $\Delta L = T_{av}.t$. Torque, in turn, is the product of force and its moment arm, the perpendicular distance from the axis of rotation. It is extremely difficult first to generate and then to withstand the large ground reaction forces encountered at impact for difficult skills, such as the one discussed previously, and to time the touchdown with an 'optimum' horizontal distance between the feet and the centre of mass (**d**, Figure 4). If that distance is too small, the body will most likely still be rotating backward when the centre of mass passes over the feet and, as a result, the gymnast will have to take one or more backward steps to maintain balance or the gymnast may even fall. On the other hand, if the gymnast lands with too large a horizontal distance between the centre of mass and the feet, the somersaulting angular momentum may be reduced to zero when the centre of mass 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 or her hands on the floor. It should be mentioned that before the gymnast takes these steps, he or she might try other corrective actions, such as rotating the arms or excessively flexing the hips 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 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 or forward rotating landings, such as front somersaults in floor exercises and front handspring and front somersault vaults. The lower landing success rate for these vaults reported by McNitt-Gray *et al.* (2001a) may be attributed to the gymnast's reduced ability to obtain kinaesthetic feedback that results in spatial orientation to 'spot' the mat – to 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 their hips at landing. This will move the body centre of mass toward the landing foot. To slow the rotation, the mat reaction force vector has to pass behind the centre of mass and the moment arm of the mat reaction force about the hip becomes short. Therefore, one can effectively resist the mat reaction force using the hip and knee extensors to 'push' 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 the mat reaction force in the forward landing.

It should be noted that difficulties in sticking landings are multiplied when rotations about the longitudinal axis are added to somersaulting. These difficulties are linked to the associated actions necessary to remove the twisting before landing and are exacerbated when the twisting has to be stopped after touchdown. Finally, the skill and force required in combinations of skills with reversal of rotation, such as forward somersaults after backward ones, are 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; 2001a; b; 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 both static and dynamic balance. Since dynamic balance requires gymnasts to reduce their 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 mass 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 towards 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 tries involve multi-joint strategies 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 and Floor Exercises

Most floor exercise routines for both men and women consist of jumping and rotating elements interconnected by simpler transitional skills. Subsequently, most research in floor exercises examines the take-off and landing characteristics of various types of somersault, mostly backward. Hwang *et al.* (1990) investigated take-off 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 take-off 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 centre of mass 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 take-off angular momentum must be optimized.

Take-off 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. Burgess and Noffal (2002) showed that advanced gymnasts exhibited greater vertical and lower horizontal take-off velocities and shorter take-off contact times during back tucked somersaults than beginners. In addition, they found that, during take-off, the 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 and direct relationships between angular momentum in flight and vertical and horizontal take-off 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, they showed that most tilt is produced by aerial rather than contact techniques. In a gymnast-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 take-off 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, favoured by most 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 Russian somersaults, were examined by Miller and Nissinen (1987) to investigate force characteristics in relation to performance. Lastly, Brochado and Brochado (2002) examined take-off kinematic differences between front somersaults on the floor and on different trampolines.

In summary, there is a wealth of information and good understanding of somersaults' take-off requirements. Competitive landings, however, have not been studied as much and, consequently, are not as well understood, although McNitt-Gray *et al.* (1993; 1994; 2001a) 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 unit during the short contact time in both take-offs 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 tried to identify anthropometric and physical prerequisites for tumbling and vaulting ability (Bradshaw and Le Rossignol, 2004). A summary of research findings for tumbling and floor exercises is presented in Table 1.

Table 1 Summary of gymnastics research on floor exercises.

Skills	*Information on*
Back somersaults: single, double (tucked, piked, layout, layout with twists)	• Take-off horizontal, vertical velocity; take-off angles; linear and angular momentums; segmental contributions to angular momentum • Timing and duration of take-off; joint and body angles during landing • Optimization
Front somersaults	• Ground reaction forces; arm motion; joint angles and take-off timing
Tumbling ability	• Predictors (of high tumbling ability)

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; Dillman *et al.*, 1985; Kwon *et al.*, 1990; Sprigings and Yeadon, 1997; Bohne *et al.*, 2000; Takei *et al.*, 2000; Koh *et al.*, 2001; 2003), handspring vaults have received more attention. To that extent, studies by Bajin (1979), Dainis (1979; 1981), Takei (1989; 1990; 1991a; b; 1992), Takei and Kim (1992); Takei *et al.* (1996), Takei (1998), Krug *et al.* (1998), Lee (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, or correlations between high and low scored vaults. As a result, it is generally accepted that, in vaulting, running approach horizontal velocity and take-off springboard linear and angular parameters may be more important than contact parameters. However, the advent of the Yurchenko vault, in which the need to strike the take-off board accurately is accentuated because of 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 take-off while in contact with the table. It is also generally accepted that the initial take-off angular momentum is invariably reduced during contact with the table, with a portion 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 take-off velocity and distance from the table to be the principal variables affecting the outcome of the vault.

Two studies by McNitt-Gray *et al.* (2001a; b) 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 worse and that, for males and females, forward translating or forward rotating vaults were the most difficult to control. Finally, although it is widely understood that most 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 practice relying 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 or flight elements and the mechanics of associated giant swings. Some transitional techniques and an

Table 2 Summary of gymnastics research on vaulting.

Skills	*Information on*
Handsprings type of vaults	• Running and springboard take-off mechanics • Post-flight characteristics • Horse contact mechanics • Post-flight and landing characteristics • Vaulting mechanics to judges scores correlation
Yurchenko vaults	• Springboard take-off mechanics • Post-flight characteristics • Horse contact mechanics • Post-flight and landing characteristics
Hecht vault	• Springboard kinetics and kinematics • Horse kinetics and kinematics • Pre-post-flight kinematics
Preceding sprint	• Average/maximum speeds for males and females
Vaulting ability	• Predictors (of vaulting ability)

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 swing. Additional kinematic, kinetic and EMG data for giant swings have been reported by several 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 using 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 and maximum height are 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 centre of mass 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.

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 maximum values and timing of various 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 and 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 bar-gymnast energy exchange varies depending on the apparatus, the sex of the gymnast 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, particularly 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 research studies mentioned above included also giant swings, flight elements and dismounts performed on the uneven bars. In addition, studies of the overgrip giant swing (Witten *et al.*, 1996), overgrip and undergrip dismount giants (Prassas *et al.*, 1998), and uneven bar dismounts (Prassas, 1996; Sands *et al.*, 2004) have been undertaken.

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 – a '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 from the high bar or uneven bars, regardless of the inertial properties of the gymnast, partly by including an atypical and larger range of motion of the centre of mass 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.

Table 3 Summary of gymnastics research on horizontal bars and uneven bars.

Skills	*Information on*
Giant swings: Overgrip, Undergrip, Inverted, Dismount	• Joint angles; angular momentum; kinetic energy; force on the bar; power; joint torques; timing; EMG activity; optimization
Release/regrasp skills: Gaylords, Tkatchovs, Gingers, Kovacs, Kolman, Pegan Marinches	• At release and regrasp and in-flight: joint angles; radius of gyration; angular momentum; take-off angle; flight and regrasp descriptors • Preparatory giant swing requirements: kinetic energy; centre of mass velocity; angular momentum; joint and body angles; optimization
Dismounts	• Take-off mechanics: linear velocity; centre of mass position; body configuration; angular momentum; kinetic energy • Optimization • Landing mechanics: body configuration; body angle
Kip	• Centre of mass trajectory; hip and shoulder joint angular velocity, torque and power

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 large part of gymnasts' routines. Research, however, has not progressed equally. For the still rings, Nissinen (1983) (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: 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'; the hip flexors' primary role is to prevent hip joint hyper-extension, whereas the primary source of energy is the shoulder musculature; and 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-feldge 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 most 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. They concluded that the outer grip has advantages over the inner by elevating the body's centre of mass more at regrasp. Liu and Liu (1989) presented a case study on swings in the extended hang. 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 (Prassas, 1994) and the backward somersault dismount (Prassas, 1995b). The dynamics of both skills have been investigated by Prassas and Papadopoulos (2001). Differences in vertical and horizontal forces during the upward, push-off 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.

Miscellaneous Research

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; this suggestion is highly unlikely to be adapted by gymnastics' governing bodies. Knoll (1996) found that gymnasts use the same biomechanical mechanisms in the performance of acrobatic tumbling exercises on floor and balance beam, giving a trade-off between take-off angular momentum and take-off linear velocities.

The pommel horse is considered one of the most difficult apparatuses; 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). The researchers concluded that, although the kinematic results suggested that the former skill may be more difficult, the fact that gymnasts perform the Magyar spindle less frequently

Table 4 Summary of gymnastics research on rings and parallel bars.

Skills	*Information on*
Parallel Bars	
Back toss	• Take-off velocity; angular momentum; body position and configuration • Upswing dynamics
Feldge mount	• Body configuration; body position; linear and angular velocity • Inner and outer grip differences
Front somersaults	• Linear and angular momentum of push off swing
Dismounts: Layout, double	• Take-off velocity; angular momentum; body position and configuration; joint angles and range of motion • Upswing dynamics; maximum (flight) height • Landing joint angles
Rings	
(Giant) swings	• Reaction forces; body configuration; optimization solutions to remove residual swing in the handstand
Dismounts	• Twisting techniques (contact vs. aerial) and segmental contributions
Double salto without releasing the rings (O'Neill)	• Centre of mass velocity and displacement; timing

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.

FUTURE BIOMECHANICAL RESEARCH IN GYMNASTICS

Gymnastics provides almost limitless possibilities for the study of human motion, but this also makes gymnastics extremely frustrating because skill selection for a study can be daunting. The nature and complexity of human movement necessitates the undertaking of many studies to understand even one activity or skill, such as locomotion. Consequently, gymnastics, with its hundreds of skills, would require very many studies before it is completely 'understood'. Attempts at devising gymnastics taxonomies have largely failed because of 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. Below are some factors to be considered.

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

Table 5 Summary of miscellaneous gymnastics research.

Skills	*Information on*
Pommel Horse	
Magyar spindle	• Joint angles; segment angular velocities
Thomas flair spindle	• Same as above
Balance Beam	
Dismounts	• Ground reaction forces
Floor/Balance beam tumbling skills comparisons	• Angular momentum • Take-off velocity

- understanding of existing techniques
- new skill development
- increase in safety
- equipment design or modification
- 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 bars be?
- how springy should a floor or a spring board be?

are those for 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 and analysing motion and is needed as a first step to skill simulations. Scientific efforts, however, that try to develop principles applicable to a wider range 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 issues related to data collection, as in the following sub-sections.

TWO-DIMENSIONAL OR THREE-DIMENSIONAL?

Whether a study should be two- or three-dimensional should be primarily determined by the skill to be analyzed. Since most gymnastic skills – or a phase within most skills – involve complex rotations, the norm should be three-dimensional. In the case of two-dimensional analysis, frame-based camera calibration method such as two-dimensional direct linear transform (2-D DLT; Kwon and Fiaud, 2002; Brewin and Kerwin, 2003) provides several advantages over the simple scaling method. First, the camera does not have to be set perpendicular to the plane of motion and, secondly, multiple cameras can be used to improve the analysis accuracy or to increase the relative image size. The camera calibration method is more suitable for the competition setting since it has fewer restrictions on camera placement. In general, the size of the calibration object is important. The control volume defined by the calibration object must be large enough to embrace the motion volume. Use of apparatuses of known size (Yeadon, 1994) or range poles (Kwon, 1996) can easily increase the control volume.

IMAGE SIZE

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

SAMPLING (OR FRAME) RATE

For practical reasons, 50 or 60 Hz with de-interlacing or field separation has been the norm in most previous research. Although these sampling 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 take-offs and landings and release-regrasp skills where body configuration changes abruptly. Results of skills or critical phases lasting fractions of a second cannot be valid when the time interval between data points is as large as 1/50 s. Although improving, the cost of high-speed video cameras still remains the main obstacle. The gymnastics investigator is often constrained by lighting in indoor venues and poorly illuminated gymnasiums. Shutter speeds are usually a compromise between obtaining a higher frame rate and maintaining a visible performer. 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, particularly in competition.

Future research will also need to consider some important issues in analysis, as follows.

SPECTATOR OR GYMNAST PERSPECTIVE

The conventional approach has been the spectator – the global – perspective. Describing biomechanical quantities in the spectator perspective often has limitations for the usefulness of the research findings since these are mostly the effects of posture control by the gymnast and the gymnast-apparatus interaction. Using 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 US Olympic Training Centre, 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 gymnasts with a view of their position as judges or spectators would see them. This type of feedback has already shown promising results.

DESCRIPTIVE OR EXPLANATORY RESEARCH?

Another main problem in gymnastics research has been that much of it has been essentially descriptive. Selected biomechanical quantities, mostly kinematic, at key events – meaningful instants – or phases have been used in correlation analyses or comparisons among groups of different skill. 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 cause-and-effect relationships in gymnastic performances. It is necessary to shift the focus of research to postural control by the gymnast and the gymnast-apparatus interaction. The muscular efforts required by gymnasts for successful and accurate postural control and interaction with the apparatuses must be studied in depth. In simple symmetrical movements, the gymnast-apparatus interaction can be analyzed easily, based on the acceleration of the centre of mass of the body. In complex movements, efforts must be directed towards instrumentation of the apparatuses to measure directly the gymnast-apparatus interaction.

THE BIG PICTURE OR MORE DETAIL?

Most previous gymnastics research has been descriptive and focused on the inter-relationship among selected biomechanical quantities, looking at the entire movement segment. This approach provides an advantage in 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 at performance enhancement require more than the 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 post-flight, such as the vertical velocity of the body centre 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 at least 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 the linear and angular velocity of the gymnast's body – the table contact conditions. 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 favourable than others; the findings may be generalizable. Since the table contact conditions 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 future research efforts.

COMPUTER 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 understand better 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 used. 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.

STATISTICAL ANALYSIS ISSUES

The ratio between sample sizes and experimental variables to be analyzed is typically dictated by statistical rules. This does not preclude the study of unique or difficult skills for which the sample size may be small, or even confined to an individual gymnast. This should be acknowledged, however, and indicated as 'single-individual designs' or 'case studies'. Another more prevailing issue is that, although descriptive statistics and statistical inferences are important in generalizing 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 at key events and during movement phases and performing group comparisons among groups of different skill are statistically convenient; however, these approaches may not effectively address the continuity of the gymnastic movement segments under investigation. Besides, it is usually difficult in biomechanical research to meet the normal distribution assumption upon which most statistical models are based. Therefore, applying statistical tests without considering the nature of the movement under investigation must be avoided.

DEVELOPMENT AND SHARING OF RESEARCH TOOLS

Interactive and easy-to-use monitoring and simulation-optimization software packages would be valuable tools for both researchers and practitioners – coaches and athletes. A substantial effort should go in 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).

COLLABORATION WITH COACHES AND OTHER INVESTIGATORS

In the USA, at least, 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 because of these issues and to constantly changing skill performances and the sheer number of skills to be analyzed. Moreover, gymnastics research has also suffered from a lack of collaborative effort 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 gymnasts is clearly a more modern model for the conduct of gymnastics-related research.

SUMMARY AND CONCLUSIONS

The body of research into gymnastics is substantial and growing. Most, however, is still skill oriented with few attempts at generalization. As a result, our understanding of the principles and bases of the sport is limited, with gaps in knowledge about technique attributes that can permeate the sport. For that reason, this review began with an attempt to identify important performance variables contributing to successful performance. We suggest that, in future, scientists should find a way to communicate a greater portion of the existing and new information to practitioners – the coaches and gymnasts. This information should be presented to the practitioners in a meaningful and understandable form. 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 should be individualized.

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