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CREATING AND RETAINING ANGULAR MOMENTUM DURING TAKE-OFFS AND REBOUNDS IN TECHNICAL/ACROBATIC SPORTS

Abstract
A biomechanical mechanism is described in airborne skills performed after preparatory skills, using gymnastics as an example of a technical/acrobatic sport. This mechanism is an optimization of somersault height and angular momentum, as well as a resultant counter angular momentum during the transition movements (take-off, rebound, blocking, releases), reducing the initial angular momentum about the transverse axis. Regarding somersault angular momentum, airborne skills are considered to be either skills with large angular momentum (e.g. layout double somersault) or skills with small or medium angular momentum (e.g. tucked double somersault). Consequently, there are different techniques for the preparatory skills that are, moreover, influenced by the initial velocity, as well as the strength of the gymnast.

1. Introduction and Problem Statement

Airborne skills with multiple rotations around the body axes are exceptional features of technical/compositional types of sports. A triple salto in gymnastics, a quad leap in ice-skating, or a four-and-half salto in diving are spectacular performances, and are viewed with amazement by the fans. This is also true for the related sports of the group, such as sport acrobatics, trampoline, and freestyle skiing. This group of sports places great demands on coordination because of the many kinds of movements. This group of sports also has an artistic/aesthetic aspect, although differently expressed in each event. Among others, both characteristics determine the subjective evaluation of the athletic performance, which because of a code of points that has difficulty tables for the skills and jumps, still has a broad, objective basis. This fact that the acrobatic characteristics have moved to the forefront, a process that has been going on for many years, and which can be objectively shown by the increase in difficulty of the optional routines (see Fetzer, 2000; Knoll & Köthe, 2000; Krug, 1996), has made Stark (1978) suggest that the "composition" name of these kinds of sports be replaced with "acrobatic". This certainly better describes what is typical with these types of sports.

Saltos with and without twists around the long axis of the body have a decisive influence on the competition result. Therefore, it is very necessary for the biomechanics scientist to study airborne skills to answer the question of how these rotations around the body axes occur. In this case, the general subject is the creation of force during the ground or equipment contact phase of the preceding, force creating movements, for example during the take-off. These preceding skills, which are barely evaluated by the judges, and ignored by the fans, have an enormous importance for the flight skills that follow them.

Even today, many athletes, coaches, and instructors are largely ignorant of the theoretical foundations of twisting skills, the saltos with twists. Even obviously educated people such as physicists or students in technical subjects can be uncertain. This is how, in a survey of 59 physicists done during the late 1970s at a University in the USA, the question if a rotation around the long axis of the body could be initiated without an initial angular impulse, in free flight, was answered by 56% with no, in other words incorrectly. As a reminder, in 1894, over 100 years ago, the French Academy of Sciences started and completed a study of this problem of how a cat falling towards the floor on its back can land on its feet, and how this phenomenon can be reconciled with the law of conservation of momentum (Cerutti, 2003). By the way, Brock (2002) showed a clear series of pictures of a falling and twisting cat during his physics lectures. On the other hand, there are hardly any questions about the mechanics of saltos with or multiple rotations around the transverse axis due to the simplicity of the subject. Nevertheless, it is difficult to communicate to sports in practice that when there are skills performed prior to a salto with rotation around the transverse axis, and therefore an initial rotational impulse during the takeoff or release, no (additional) salto angular impulse is created. Instead, the salto angular impulse is decreased, in some cases by quite a lot. From the point of view of mechanics, this is just a simple application of the impulse law taking into account the initial conditions, in this case to an angular impulse analogous to translation. In the gymnastics literature, there have been publications for over 20 years on the decrease in angular momentum during the take-off/release after skills preparatory to saltos with one and multiple rotations (Heß, 1979; Knoll, 1981, 1993; Parlak, 1975).

It has been, and is still the case, that the skills performed preparatory to airborne skills with salto and twist rotations show functional relationships. These relationships probably cover all gymnastics events and several disciplines in the sport type-group and could be considered to be "Biomechanical Principles" in the sense meant by Hochmuth (1981). This seems necessary given the multitude of skills as well as the continual and permanent need in the technical-acrobatic sports to find the most appropriate techniques and create new skills and jumps.

The rest of this discussion concerns airborne skills performed from preparatory skills in gymnastics. We investigated which mechanisms were acting when dismounts and airborne skills were performed following preparatory skills, as opposed to from a still stand. The results are presented with selected examples. The principles are applicable to similar sequences of movements in related sports and disciplines.

2. Methods

Two dimensional photographic methods were used to collect the necessary data and parameters. Three dimensional methods were used only in selected cases. The video and still pictures (50, respectively 48 Hz frequency) were analyzed with the two dimensional pictorial measurement method of Drenk (1988; 1994). Calculation of the center of mass of the body was based on a 10 segment model. The relative mass, length, and center of mass parameters of each segment were based on a method by Hildebrand and Nicolaus (1980) that respected the typical body characteristics of gymnasts. The relative inertial radii came from Zatsiorski, Aruin, and Selujanov (1984). Calculation of the mass inertial moment and angular impulse of the transverse axis was done according to Hay, Wilson, and Woodworth (1977) due to the fact that most of the movements were performed in the sagittal plane.

Parameters were recalculated to unit values in order to compare the contributions of inertial moment, angular impulse, and energy between athletes with different body mass and size. The basis for this reduction is the linear proportionality between the segment lengths and the body length in the population studied.

In addition, force measurements, synchronized with the photography, were made on the high bar, rings, uneven bars, vault table, and floor. With the exception of the floor exercise, on the other gymnastics equipment, force measurements could also be made during competitions, the 1994 World Championships in Dortmund and 1997 in Lausanne. The floor measurements were made at a special location with force plates. Force sensors, using the principle of electrical resistance measurement, were added to the gymnastics equipment with the help of the gymnastics equipment manufacturer Spieth in Esslingen (Knoll, 1999). They were installed and calibrated so that changing grip locations on the uneven bar rail or high bar, changes in uneven bar tension, and rail adjustments could be taken into account.

3. Results

The following structure was set up for the complete movement sequence of preparatory and flight skills (see Table 1):

1. Preparatory skills
2. Transition movement(s) in the form of takeoffs (from the feet), blocking off the hands, and bar releases
3. Airborne skills (with rotation around the body axes)
4. Landings

Table 1. Movement structure and effective biomechanical mechanism

Movement Structure	**Preparatory Skills**	**Transition Movement(s)**	**Airborne Skills**	**Landing Movements**
Function	Create energy	Transform energy	Rotation around the body axis	Absorb energy
Functional element	For example, back handspring, back giant, sprint and take-off	- Take-off - Blocking - Swing	Salto and twisting; for example, half in-half out	
Main biomechanical parameter	Initial angular impulse (**L**A)	Counter angular moment (**M**)	Salto angular impulse (**Ls**)	

The task to be completed during preparatory movements is to create enough kinetic energy for the airborne skill. Depending on the gymnastics event, the kinetic energy created is present in different forms at the end of the preparatory skill, in other words immediately prior to the transition movement(s). On the floor for example, a considerable horizontal translation is present at the end of the round-off, back handspring, salto acrobatic series up until the transition movement, the salto take-off, in addition to the rotation around the transverse axis of the body. This horizontal motion is almost totally absent in the still rings. But the skills or partial skills of the preparatory movements have something in common at the end of their functional period: they all have a rotation around the transverse axis.

Consequently, we calculated the angular impulse **L** around the transverse axis and compared its contribution prior to and after the transition movement[1]. The angular impulse **L** is the product of the mass inertial moment **J** and the angular velocity $\boldsymbol{\omega}$ (and is expressed in units of kilogram meters squared per second):

$$L = J\,\omega \quad [kgm^2/s]$$

Comparing the angular impulse before and after the transition movement, in many examples from gymnastics the take-off, blocking, or release shows that the salto angular impulse $\mathbf{L_S}$ is always smaller than the initial angular impulse $\mathbf{L_A}$. Formally

$$L_S < L_A$$

Consequently, subsequent to the angular moment impulse, the impulse law analogous for angular movements, a resultant angular moment **M** must have been acting during the transition skill counter to the direction of rotation - a negative angular moment that reduced the initial angular impulse:

$$\int_{(t)} (-M)\,dt = L_S - L_A$$

In order to compare the various rates of reduction across combinations of flight skills and gymnastics events, the ratio of salto to initial angular impulse was calculated and named angular impulse retention quotient (**q**):

$$q = \frac{L_S}{L_A} \qquad (q < 1)$$

This quotient, which is always less than 1.0, ranges between 0.11 -0.95 depending on the flight skill investigated on the various gymnastics equipment with corresponding transition skills

Floor, balance beam => take off
Vault, parallel bars => blocking
High bar, uneven bars, rings, parallel bars => release

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[1] The angular impulse L and other parameters are exclusively for the transverse axis and therefore not subscripted.

The minimal value of **q** = 0.11, in other words the lowest rate of retention of the angular impulse was observed in the straddled flyaway dismount from the rings. The upper range was for the Yurchenko vaults with **q** = 0.8 - 0.95.

Observing the contributions of the angular impulse around the transverse axis during airborne skills in various gymnastics events, two groups get identified, independent of any additional longitudinal rotation (twist). On the one hand there is a group with large angular impulses represented typically by the layout double salto and on the other a group with small to average angular impulses, typified by the tucked double salto. Consequently, the important differentiating characteristic is the body shape, or mechanically, the mass moment of inertia. This mass moment of inertia increases by up to a factor of four when moving from a tight tuck to a layout (arms down). This great mass moment of inertia is therefore the origin of the greater angular impulse during layout double saltos.

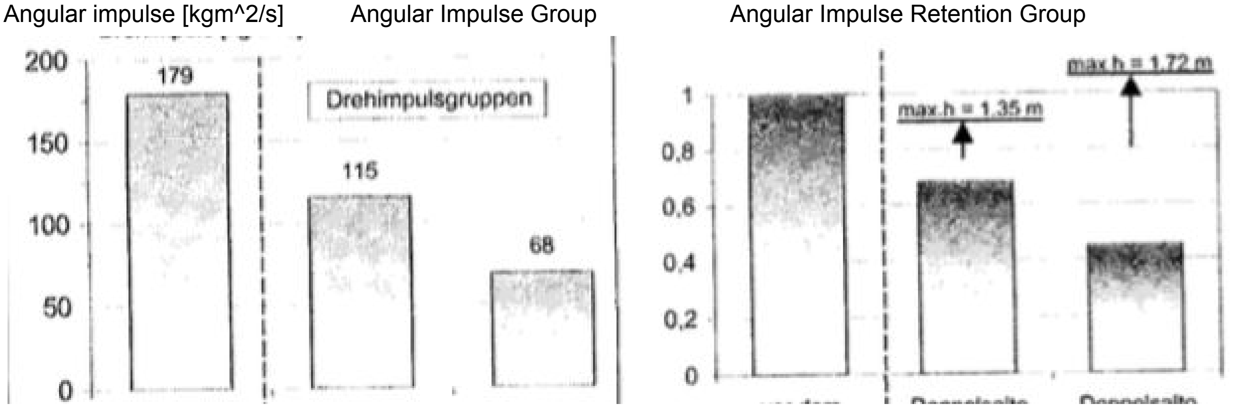
All of the double saltos performed with a layout on the floor, high bar, uneven bars, rings and vault belong to the angular impulse group "**layout double salto**". Strictly speaking, double saltos on the arm events involve only 1 1/2 - to maximum 1 3/4 saltos while the skill known as handspring front or back salto vault off the vault table, or previously the vaulting horse, actually is a 1 and 1/2 salto. In addition to all tucked double saltos, the angular impulse group "**tucked double salto**" surprisingly also includes the tucked triple saltos as well as single saltos in various forms, tucked, piked, or layout. The piked double salto has an intermediate position. These angular impulse groups have a further differentiating characteristic in addition to the contribution of the angular impulse: the height attained in flight, or more precisely the elevation of the center of mass of the body (COM), or the difference between the height at take-off and the top of the flight trajectory. Assuming equivalent initial energy conditions and strength abilities, the airborne skills in the “smaller angular impulse" group can be performed with greater height. And correspondingly, airborne skills in the "greater angular impulse" group can only be performed with lower salto height. Of course, male and female gymnasts with better physical abilities and eventually technical prerequisites are more capable of, for example, tumbling a layout double salto during the floor exercise than a less favorably gifted athlete can do a tucked double back salto. But these important, functional relationships do not permit the same gymnast to perform a salto with the greater angular impulse higher than a salto with the lesser angular impulse under the same initial conditions.

Examples after a round-off, back handspring on floor of angular impulse groups, angular impulse maintenance quotients, and maximal flight height are shown in Figure 1. The blocking action during the take-off to a triple back off the floor produces a maximum height measured at h = 1.72 m while the take-off to the full-twisting layout double back salto, which retains more of the initial angular impulse, gave a maximum height of only around 1.35 m.

Reduction of the angular impulse can be considered to be part of a biomechanical mechanism. Therein, functional relationships are understood that are typical for this sequence of movements, namely the airborne skills with great height, performed after preparatory skills. Besides the reduction, this mechanism also involves an optimization aspect in such a manner that, in summary

- The reduction aspect consists in reducing the angular impulse during the transition movement (take-off, blocking off the hands, bar release) to an airborne skill, the effect of the resulting counter angular impulse.
- The optimization aspect involves optimizing the angular and vertical impulses during the transition movement according to the reigning initial conditions and the requirements of the flight phase. The initial conditions include the orientation and angle of the body to the floor, and its velocity, in translation as well as in rotation. The requirements of the airborne phase include the number and kinds of saltos, whether tucked, piked, or layout.

Angular impulse [kgm^2/s] Angular Impulse Group Angular Impulse Retention Group



Prior to Take-off | Layout Double Back | Tucked Double Back | Prior to Take-off | Layout Double Back | Tucked Double Back

Figure 1. Angular impulse groups, angular impulse maintenance quotients (**q**), and maximal flight height (max. h) following a round-off, back handspring, and different saltos during a floor exercise tumbling pass.

Mentioned in the problem statement, and still widely believed even today, is the belief that the backwards rotating angular impulse is <u>increased</u> during the take-off to a salto from a back handspring. This erroneous belief apparently comes from confusion with the conditions during a standing back salto (see Figure 2.). Confusion begins with the fact that often the analogous mechanical values and laws for rotating movement are unknown and seem to be somewhat more difficult to understand. While the impulse law or the impulse for translation is well known

$$\int_{t_1}^{t_2} F\,dt = p_2 - p_1 = m(v_2 - v_1)$$

Subscript 1: preparatory skill
Subscript 2: salto

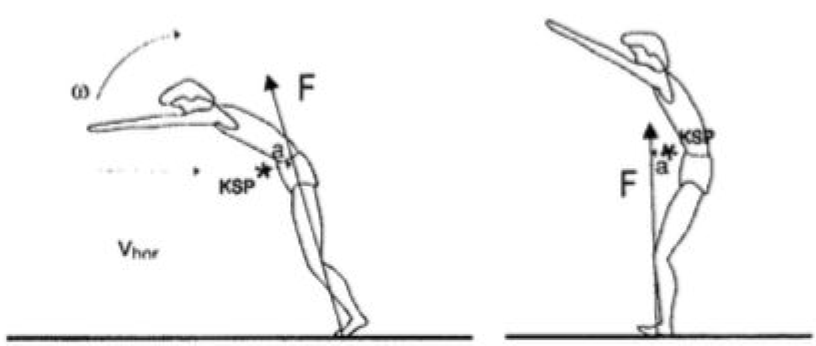
this is hardly the case for the angular impulse during rotation:

$$\int_{t_1}^{t_2} M\,dt = L_2 - L_1 = J_2\omega_2 - J_1\omega_1$$

Taking into account the initial values for the integration, and the fact that the kinetic analyses always give a reduced value for the **L2** salto angular impulse, in other words that **L2** < **L1** is valid, then

$$\int_{t_1}^{t_2} (-M)\,dt = L_2 - L_1$$

has a negative sign for the resulting angular moment. Consequently, there is an angular moment against the direction of the initial angular impulse - a counter angular moment. The investigations of acrobatic tumbling series with force plates confirmed this principle direction of the vector of the floor reaction force during salto take-offs (Knoll, 1981).



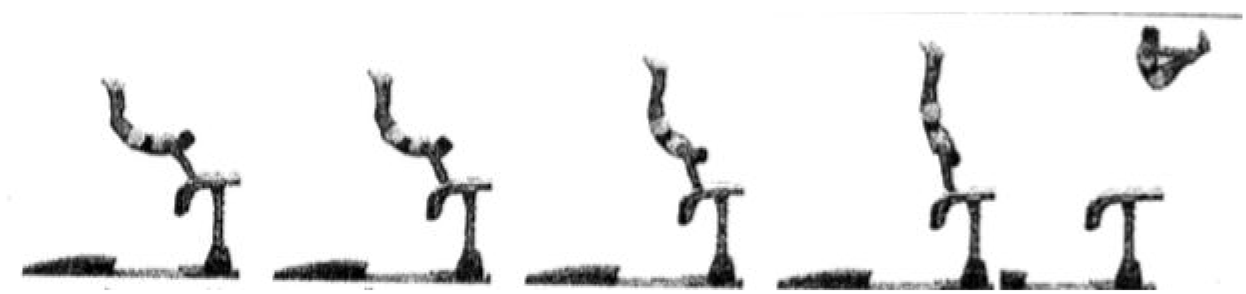
Take-off after a round-off, back handspring
M acts counter to the direction of rotation
Angular moment **M** = Fa

Standing take-off
M acts backwards

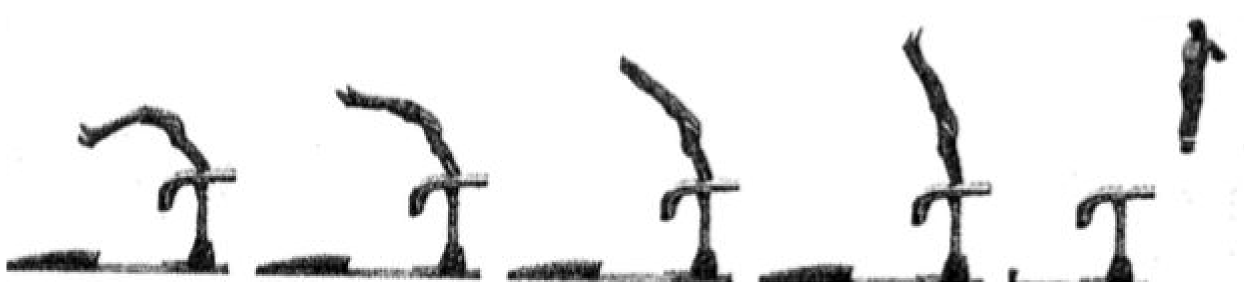
F = force
a = lever arm

Fig. 2. Schematic presentation of the floor reaction force during salto take-offs, from a tumbling series (left) and from standing (right).

The reduction of the angular impulse, and thereby closely associated optimization of the vertical impulse, in other words the jump height, occurs dependent on the angular impulse necessary for the salto and on the anatomical particularities. The influence of the anatomical particularities that arise during forwards and backwards movements are clear in the shoulder joint during the block of vaults off the table. Comparison of the shoulder joint angle during the block of a handspring forwards and a handspring backwards (Yurchenko) clearly shows a greater change in shoulder angle in the one and in the other a fixation of the joint at a constant angle (see Fig. 3.). The block on the table during a handspring forwards in the upper photo series offers the opportunity for a greater blocking effect and thereby a greater reduction in angular impulse.



=> Blocking off the table to a front handspring and piked double salto



=> Blocking off the table to a back handspring, layout 2 3/2 twists (Amanar)

Fig. 3. Different anatomical limitations in the blocking technique off the vaulting table during forwards and backwards handsprings (extended or closed shoulder angle versus (hyper-) flexed shoulder angle).

Comparing the take-off to a back triple salto and a layout double salto, each tumbled from a round-off, back handspring, reveals the effect of the angular impulse necessary for the salto rotations on the rate of reduction of this angular impulse during the take-off, and thereby on its creation (Fig. 4). The layout double salto requires a considerably greater angular impulse compared to the tucked triple salto. Assuming similar initial velocities, the take-off to the layout double salto must have less of an angular impulse reduction. This fact is reflected in the body positions and shape in Fig. 4 (lower photo series), among others in the body position relative to the vertical. In contrast, the take-off to the triple salto shows a blocking action and consequently a stronger angular impulse reduction (upper photo series).

The blocking take-off to the tucked triple salto, which has only an intermediately large angular impulse contribution, leads to a higher salto height. On the other hand, a take-off with just a small blocking action, such as the layout double salto, results in only an intermediately high salto height. This is the previously mentioned optimization problem.

In general, we can note that transition movements with a strong reduction in angular impulse lead to higher salto heights, assuming the same initial velocity and same strength abilities.

Take-off to a tucked triple back salto

Take-off to a layout double back salto

Fig. 4. Different take-off techniques on floor according to salto angular impulse during a tucked triple back salto and a back layout double salto (intermediate compared with greater angular impulse).

5. Summary and practical consequences

The relationship presented here can be summarized under two aspects for airborne skills performed after preparatory skills with the goal of great salto height in the example of gymnastics. This consists of

1. in the creation of a maximal vertical impulse out of the available angular impulse around the transverse axis of the body as well as the horizontal impulse, while simultaneously setting up a sufficient salto angular impulse - an optimization problem, and
2. in the appearance of a counter angular moment during the transition movement, reducing the initial transverse angular impulse - presented as the angular impulse maintenance quotient **q**.

Airborne skills can be classified in two groups according to the contribution of the transverse axis angular impulse. One is the "layout double salto" group with large angular impulses and the other is the "tucked double salto" group with low to intermediate size angular impulses. The mechanism presented here is clearly reflected in the technique of the transition movements (take-off, block, release) of the two angular impulse groups. Consequences can be derived from these biomechanical mechanisms for appropriate or virtuous airborne skill technique and their preparatory skills

The fact of an angular impulse reduction during the transition phase requires the highest possible velocity at the end of the preparatory skills. When there is a high initial potential, after the reduction there is still a correspondingly greater remainder that can be used for the airborne skill. (An exception consists of the airborne skills with counter rotation (hecht), for example the tkatchev bar release skill). Performing single saltos with virtuoso technique, which means above all maximal height, also requires a high initial velocity. The necessary, more powerful angular impulse reduction can be performed by changing body and spatial angles. The necessary strength is assumed.

Given the fact of a smaller reduction in angular impulse prior to flight skills with a greater angular impulse (the "layout double salto" group), one can imagine that an increase in the number of salto rotations would also be possible by increasing the angular impulse maintenance quotient **q**. Besides increasing the height or flight duration, here is therefore, in principle, another solution for increasing the number of saltos and thereby creating new skills.

References

Brock, I.C, (2002). Physik I für Nebenfächler [Physics for non-specialists]. Kap. 11. Zugriff am 20. März unter http://zina06.physik.uni-bonn.de/-brock/teaching/pnfl ws0102/chapter 11.html

Cerutti, H. (2003). Von Tieren - Warum Katzen stets auf die Füße fallen [About animals - why cats always land on their feet]. iff am 20. Ocktober 2003 under http://wwwx.nzz.ch/folio/archiv/2003/05/articles/tiere.html

Drenk, V.(1988). Erarbeitung von photogrammetrischen Auswertverfahren für den einsatz schwenbarer Kameras in the Leistungssportforschung. [Development of photo-metric methods for the use of pannable cameras in high performance sports research]. Dissertation. Leipzig: Forschungsinstitut für Körperkultur und Sport.

Drenk, V. (1994). Photogrammetric evaluation procedure for pannable and tiltable cameras of variable focus length. In A. Barabas & G. Fabian (Ed.), Proceedings of the 12th International Symposium on Biomechanics in Sports (pp. 27-30). Budapest: ITC Plantin, Publishing and Press Ltd. Company.

Fetzer, J. (2000). Analyse der Weltmeisterschaften im Kunstturnen 1999 (Männer). [Analysis of the Artistic Gymnastics World Championships 1999 (Men)]. Leipzig, Institut für Angewandte Trainingswissenschaft.

Hay, J., Wilson, B., Dapena, J. & Woodworth, G. (1977). A computation technique to determine the angular momentum of a human body. Journal of Biomechanics, 10, 269-277.

Heß, R. (1979). Untersuchungen zur Technik des Handstützsprungüberschlages mit Salto vorwärts unter besonderer Berücksichtigung der Darstellung von Zusammenhängen zwischen dynamischen und kineatischen Parameteren des Abdrucks - ein Beitrag zu Leistungsdiagnostik und Trainingssteuerung im Stützsprung [Investigation of the handspring with forwards salto technique with particular attention to the relationship between dynamic and kinematic parameters of the blocking action - a contribution to performance analysis and training control in vaulting]. Dissertation, Halle-Wittenberg: Martin-Luther-Universität.

Hildebrand, F. & Nikolaus, R. (1980). Eine Möglichkeit zur Verbesserung der

Bestimmung der Lage des Körperschwerpunktes und der Lage der Teilschwerpunkte des menschlichen Körpers. [A method to improve determination of the position of the center of body mass and human body segment center of mass]. Theorie und Praxis Leistungssport, 18 (3), 70-82.

Hochmuth, G. (1981). Biomechanik sportlicher Bewegungen (4. Auflage). [Biomechanics of athletic movement, 4th edition]. Berlin: Sportverlag.

Jonglieren-Hamburg.de (2003). Zugriff am 20. Februar 2003 unter http://www. Jonlieren-hamburg.de/bestOfMailing/salto Physik.txt. [Salto physics].

Knoll, K. (1981). Zur biomechanisch zweckmäßigen Technik von Flugelementen im Gerrätturnen - dargestellt om Beispiel von akrobatischen Rückwärtssprüngen am Boden und von Abgängen an den Ringen. [On appropriate biomechanical technique of flight skills in gymnastics - presented with the example of acrobatic backwards flips on floor and ring dismounts]. Dissertation, Leipzig: Deutsche Hochschule für Körperkultur.

Knoll, K. (1993). Zum biomechanischen Wirkungsmechanismus von Flugelementen aus vorbereitenden Bewegungen und Ableitungen für die Technik von Rondat und Flick-Flack am Boden. [Biomechanical mechanisms of flight skills performed after preparatory movements and consequences for the technique of the round-off and back handspring in the floor exercise]. In G.-P. Brüggemann & J. K. Rühl (Hrsg.), Biomechanics in Gymnastics (s.115-126). Köln: Sport und Buch Strauß.

Knoll, K. (1999). Entwicklung von biomechanischen Messplätzen und Optimierung der Sporttechnik im Kunstturnen. [Development of biomechanical measurement stations and optimization of gymnastics technique]. Köln: Sport und Buch Strauß.

Knoll, Kl., Knoll, Ka. & Köthe, T. (2000). Grenzen der Leistungsfähigkeit des Menschen aus der Sicht technisch-kompositorischer Sportarten. [Limits of human performance capacity from the point of view of technical compositional sports]. Leistungssport, 30(1), 30-38.

Krug, J. (1996). Entwicklungstendezen der Trainings- und Wettkampfsysteme in den technisch-kompositorischen Sportarten. [Developmental trends in the training and competition systems in the technical-compositional sports]. Zeitschrift für Angewandte Trainingswissenschaft, 3(2), 107-121.

Parlak, J. (1975). Ocena Skuteczosci Fazy Odbicia w Skokach Akrobatycznuch z

Mierjsca i z Rozbiegu. [Evaluation of the take-off phase of acrobatic jumps from standing and running]. Gimnastyka, 5,5-12.

Stark, G. (1978). Zur Weiterentwicklung des Trainings der akrobatischen Sportarten und Disziplinen. Ein trainingsmethodisch-konzeptioneller Beitrag zur schnelleren Leistungsentwicklung einiger technischer Sportarten, besonderes des Gerätturnens. [The further development of the training of acrobatic sports and events. A training-theory contribution to faster performance progress in some technical sports, particularly gymnastics]. Habil. Schrift. Leipzig: Deutsche Hochschule für Körperkultur.

Zatsiorski, V.M., Aruin, A. S. & Selujanov, V. N. (1984). Biomechanik des meschlichen Bewegungsapparates. [Biomechanics of the human movement apparatus]. Berlin: Sportverlag.