GEOFFREY DYSON MEMORIAL LECTURE

BIOMECHANICAL CONSIDERATIONS ON JUMPING IN SPORTS AN APPROACH TO A FUNDAMENTAL UNDERSTANDING

GERT-PETER BRÜGGEMANN
INSTITUTE FOR ATHLETICS AND GYMNASTICS, GERMAN SPORT UNIVERSIY, COLOGNE, GERMANY

INTRODUCTION

In the introduction to the seventh edition of "The Mechanics of Athletics" Geoffrey Dyson mentioned the importance of increased knowledge of mechanical principles in the development of track and field athletics coaching. Dyson focussed on the knowledge of mechanics - or biomechanics - as an essential tool with which to distinguish between important and unimportant, correct and incorrect, cause and effect, possible and impossible (Dyson 1978, 12). From his principal concept Dyson was ahead of most biomechanists of his time, who often reduced the human body to the simple CM-model (CM: Center of mass) dealing with sport skills, because he added to the mechanical laws other ones (e.g. biological laws, coaching and didactic principles) which - in his understanding - also play an important part in the analysis and optimization of human motion.

This paper, as a tribute to the applied research of Geoffrey Dyson and the general concept of applied research in sport biorxiechanics, will discuss biomechanical concepts to identify and explain limiting factors of jumping in different sports on the background of their usefulness for coaching and performance optimization.

On the basis of this general aim the paper presents an attempt of a fundamental understanding of the take-off movement and thus considers such factors which - apart from their relevance for the actual performance in sport - comply with the criterion that they are controllable, trainable and thus transferable into the practical process of training. In the field of sports jumping often comprises the entire performance e.g. the high jump, the long jump or double backward somersault. Thus jumping events are composed of (1) the preparatory approach, (2) the take-off (3) the flight and (4) the landing.

In the following the focus will be on the take-off phase, that is to say on the transition phase, which enables the athlete to transfer the initial mechanical conditions to the mechanical properties at take-off. These are the determining mechanical factors for the following flight. Therefore the beginning and the end of the transition phase are the instants of touchdown of the support leg (the first contact with the ground) and the take-off of the support leg (the last contact with the ground).

A CONCEPT FOR THE STRUCTURING OF JUMPING IN SPORTS

Jumping skills in sport occur in a great variety of sport disciplines showing quite different goals and forms. Before starting with the biomechanical aspects of jumping, it seems necessary and sensible to classify and structure the different shapes of jumps. The mechanical aims of the take-off phase can be formulated as an optimum production of the body's take-off velocities. Intentionally, the term optimum and not maximum take-off velocities has been chosen. This accounts for the fact, that translation and rotation are of great importance to movements in sport or more precisely to flights in jumping. The mechanical take-off properties considered have to examine linear and angular velocities. This also accounts for'the fact, that under a given dependence of the specific aims of the jumps the linear and angular velocities must be optimally proportional to each other. Thus the specific aims of individual forms of jumps present one way of approach to structure the skills. In a great number of jumps the production of a maximum height of flight and thus a maximum vertical take-off velocity of CM can be deduced as the intrinsic purpose of the take-off. Examples are the vertical jumps for blocking in volleyball or for a rebound in basketball.

In the athletic horizontal jumps i.e. the long and the triple jump horizontal and vertical takeoff velocities are maximized when examined individually but optimized in their relation to one another. Thus both velocity components underly a trend towards optimization. Other jumps are combined with rotational requirements, i.e. with an angular momentum for the realization of their aims. Vertical take-off velocities of CM and angular momentum have to be in an optimum relation, in regard to the specific purpose. Examples are the Fosburyflop and double backward somersault in tumbling.

According to their primary intention these categories of aims in jumping events can be identified in regard to their mechanical take-off properties:

Category 1: Maximum vertical velocity of CM

Category 2: Optimum vertical and horizontal velocity of CM

Category 3: Optimum vertical CM's velocity and angular momentum.

As further criteria for the structure the mechanical and anatomical, respectively the biomechanical conditions for the take-off can be considered. Therefore take-offs from elastic surfaces must be differentiated from take-offs from solid ones. Furthermore one-leg take-offs are to be distinguished from take-offs with both legs. This differentiation takes into account the different number of swinging segments. Both criteria appear in two different shapes each, so that there are the following four possibilities for the differentiation of takeoffs according to the mechanical and anatomical conditions.

It is remarkable, that in practical sports in most cases one-leg take-offs appear to be realized from solid surfaces, whereas take-offs from both legs are predominantly realized from elastic ones.

As a third crition the initial mechanical conditions for the take-off are chosen. Here. too, a great variety of combinations is possible, which however may be reduced to three categories under consideration of prevalent quantity:

Category A: Initial horizontal velocity of CM

Category B: Initial downward velocity of CM

Category C: Initial horizontal velocity of CM and initial angular momentum.

Without claiming completeness five classes of take-offs can be identified when applying these three identifical criteria. Jumps without substantial initial mechanical conditions and without a preflight phase like the vertical standing jump are dispensed with.

Form	Initial conditions	Surface	one/ two legs	mechanical take-off properties
TAKO I	horizontal CM velocity	solid	one	horizontal and vertical CM velocity
TAKO II	horizonal CM velocity	solid	one.	vertical CM velocity and angular momentum
TAKO III	horizonal CM velocity	elastic	two	vertical CM velocity and angular momentum
TAKO IV	vertical CM velocity	elastic	two	vertical CM velocity and angular momentum
TAKO V	horizontal CM velocity and angular momentum	elastic	two	vertical CM velocity and angular momentum

Table 1: Classification of jumps in sports

Representatives of TAKO I are the long and the triple jump, of TAKO II the high jump and of TAKO III the running forward somersault in gymnastics. TAKO IV comprises the take-offs for multiple somersaults in diving and trampolining. TAKO V is represented by the take-off for the somersaults in gymnastic tumbling with preparatory round-off and flic-flac.

At a closer consideration of the five groups it is remarkable that quite often a considerable vertical initial velocity occurs in jumps from elastic surfaces witliout initial angular momentum in addition to the dominant horizontal CM's velocity. Data refemng to this fact were first presented for the running forward somersault by Miller and Nissinen (1987) and for the running take-off in vaulting by Takei (1990).

BIOMECHANICAL STRATEGIES FOR APPROACHING AN UNDERSTANDING OF HUMAN JUMPING

Before the extracted groups of jumps can be dealt with in detail the biomechanical concepts so far applied, which supplied an approach for the understanding of human jumps will be explained.

In relevant literature five principal concepts may be differentiated, which can be called in a captious form:

1) CM concept
2) Segmental contribution concept
3) Joint moment concept
4) Elastic energy storage concept
5) Segmental energy transfer concept.

The CM-concept: The simplificatiÆn of the human body to a single point model indicated as center of mass (CM) permints the determination that the height of flight achieved in the jumps depends on the vertical take-off velocity of the CM. The take-off 'velocity is trivially determined by the vertical impulse and the body mass. Thus the vertical impulse becomes the performance determining factor.

Hochmuth (1982) formulated two biomechanical principles, which dealt with the sole consideration of the CM and the maximization of the vertical impulse.

(a) Initial force principle: The principle of the initial force, which was later termed initial power principle, states that if the purpose of take-off is a maximization of the speed of the center of mass at the instant of take-off, the acceleration force must be greater than zero at the beginning of the acceleration phase. The acceleration force and the causing muscle force increase in order to slow down the countermovement. The decreasing speed of the countermovement results in the initial force as formulated by Hochmuth. The relation of the deceleration impulse and the acceleration impulse apparently seems to show an optimal ratio. Hochmuth termed this relation as Kappa-ratio and formed an optimum of 0.3 - 0.4; that means that the optimal deceleration impulse is 30 - 40 % of the acceleration impulse.

This principle of initial force was studied in vertical jumps. The phenomenon of the potentiation of muscle force by the deceleration of a countermovement has meanwhile been explained in various places as a reflex induced potentiation and/or the storage and utilization of elastic energy during stretch-shortening cycles (Bosco et a1.1981; Bosco et al. 1982; Bosco and Komi 1979).

(b) Principle of the optimal path of acceleration: In a given human movement which requires a maximum final speed, the path of acceleration has to be of optimal length, linear or slightly curved depending upon the sport discipline and the athlete's strength abilities. This general principle enjoys an interesting application in the athletic jumping events. In order to generate an optimal long path of acceleration for the increase of vertical velocity at take-off with the aim of maximizing this velocity component while preserving horizontal speed, the elite long jumper avoids any lowering of his CM during the take-off. As CM's height at the instant of take-off largely depends upon the anthropometric measurements of the athlete and seems to be near to invariant, the top jumper pushes forward his phase of the prolongation of the path of acceleration into the take-off preparation phase. In this preparation phase a decided lowering of CM can be observed.

The **Segmental** Contribution-Concept: Miller and East (1975) added to the CM-Concept the Segmental Contribution Concept to study the role played by individual segments in producing the CM's acceleration or the vertical impulse, respectively. In the weighting phase of the take-off in a vertical standing jump **inertial** forces of the arms, legs and the trunk in relation to the total body were analyzed. This was a major advantage in regard to the **CMstrategy** and allowed a first **slight.inside** view into jumping strategies.

The Joint Moment Concept: From the Segmental Contribution-Concept the Joint Moment Concept was systematically generated for rhe very first time by Hay (1981). Arguing that the resultant joint torques determine the segmental initial force the influence of the net joint moments were related to CM's take-off velocity in vertical jumps. To apply multivariate statistics, the time of take-off was differentiated in eight sections. On the basis of the data of 194 subjects ten torques, having more than 2.9 percent variance in the take-off velocity, were extracted.

The elastic **Energy** Storage **Concept**

This concept was applied by different authors **(e.g.** Bosco et **al.,1981)** to jumps to examine the utilization of the elastic potential of the leg extensor muscles during the short stretchshortening cycle. This concept was also specifically utilized to identify training drills in regard to their adaptivity to the target performance.

The Segmental **Energy** Transfer Concept:

The changes in mechanical energy of body segments by the transfer, generation or absorption of energy by muscles **and/or** the transfer of energy through the joints was studied in human locomotion **e.g.** by Winter (1981). Under consideration of the segmental inertial and gravitational forces an estimation of energy flow into and out of a segment is possible. Thus an interaction of segmental work can be quantified. The concept was dealt with in detail by Aleshinsky (1986) and Van Ingen Schenau and Cavagnagh (1990) in endurance sports. An application **to** different jumps in sports is still missing.

APPLICATION OF BIOMECHANICAL CONCEPTS TO THE DIFFERENT GROUPS OF JUMPS IN SPORTS

In this chapter the above explained concepts will be applied **to** representatives of the five extracted groups of take-offs. The focus is set on athletics and gymnastic take-off because of an easier standardisation in regard to jumps in the **sport** games.

TAKO I. Take-off for the **longjump**

The initial mechanical conditions for the take-off primarily **refer** to run-up velocity which generates the initial kinetic energy and secondly to **the** CM's position ***at*** the touchdown into the take-off.

Data in literature show a general trend towards a maximization **of run-up** velocity. The linear correlationship between CM's horizontal velocity at **touchdown** and the official or effective distance of the jump can not be generally transferred **to individuals** especially to top athletes.

In elite longjumpers the run-up speed represents a necessary prerequisite for a successfull jump; but it does not constitute the only relevant factor for the performance. Individually the run-up speed shows an optimal trend.

Using the CM-concept the CM's position at touchdown is directed in such a way that (a) the contact foot can be placed in front of the center of mass and

(b) the vertical CM's position is lowered, in order to have a long vertical path of acceleration at disposal during the take-off.

If the center of mass is lowered in the last strides of approach and kept low at the take-off into the last stride, its trajectory in the flight prior to touchdown can be made flat. If in addition the flight time is reduced, this will lead to a minimum downward velocity at touchdown.

The vertical force or more precisely the vertical impulse produced during the take-off determines the change of vertical velocity of the CM. If the downward velocity is low the given impulse effects a larger velocity at the instant the foot leaves the ground.

This trend to minimize the downward velocity at touchdown or even to achieve an upward CM-velocity at the beginning of the take-off phase seems to be a general principle in takeoffs with initial horizontal speed and the aim to achieve sufficient vertical take-off velocity. Ridka-Dracka (1986) used the CM-concept to model the take-off and calculate the effect of different CM positions at touchdown and run-up speeds to the mechanical take-off characteristics. The model assumed no energy loss during the take-off. This assumption cannot hold and the simulation led to unrealistic results.

Brüggemann and Nixdorf (1985) presented empirical data of total body energy changes during the longjump take-off which indicated an energy loss of approximately 6 % during the take-off phase for elite male longjumpers. These data correspond with the recently published figures of female longjumpers. Lees et al. (1993) calculated a total energy loss during the take-off of 6.7 %.

Therefore the CM-concept can contribute and even had contributed to formulate the mechanical framework for the take-off with a high horizontal run-up speed. The contribution to a principal understanding of the take-off is relatively poor (see e.g. Ridka-Dracka,1986). The segmental contribution concept allows an estimate of the effect of the swinging leg and the arm-action during take-off. The data base of segmental impulses or segmental inertial forces studied on longjumpers is very small. Thus only a first trend can be presented. The inertial vertical force of the lead leg increases immediately after touchdown and decreases distinctly before the foot leaves the ground. This could be found in the majority of elite jumpers studied during the last world championships and Olympic Games (Brüggemann, Susanka 1987). ,The inertial force pattern of the arms indicate a more stabilizing effect of these segments in order to counterbalance the lead leg activity. Summing up a simple summation of forces with a simultaneous ending of the acceleration according to Dyson's model of long and high jumping unfortunately does not hold. It seems to be too mechanistic.

Kollath (1980) used the joint moment concept to quantify the net mechanical load during the long jump take-off. This study focussed on load quantification does not contribute to an understanding of the long jump take-off.

The elastic energy storage concept was introduced in the discussion of the longjump takeoff by Bosco et al. (1975). Bosco, Luthanen and Komi figured out that the proper technical execution of the take-off should therefore rely on the utilisation of elastic energy that is stored in the muscles during the excentric (stretching) contraction at impact. If the stretching phase is too long, it should naturally lead to a reduction in the stored elastic energy (Cavagna, Dusman and Mararia, 1968). Thus it would seem logical to emphazise the importance of the gain in vertical CM velocity during the early contract period. How the athlete'is able to benefit from this take-off period depends on the ability of his leg extensor muscles to utilise the coupling of the eccentric-concentric contractions at and immediately following the impact.

Lees et al. (1993) reactivated these considerations and described the changes of mechanical energy from touchdown to maximum knee flexion and from maximum knee flexion to take-off. From touchdown to maximum knee flexion 15 % of the mechanical energy is lost from the initial kinetic energy and does not appear in a measurable mechanical form.

This energy amounts to about 350 Joule for a typical 60 kg female longjumper. Such a quantity of energy can be dissipated by negative muscular work and stored in the elastic structures of the take-off leg. With structures capable of storing at least 100 Joule in running (Ker et al., 1987) and probably more for the long jump where the extention forces are much greater, it is likely that the reutilization could play an additional role in the further increase of vertical CM velocity and take-off. Alexander and Benet-Clarke (1977) calculated that the energy storage capacity of the muscular cross-bridge linkages is in a range of 2.4 - 4.7 Joule/ kg muscle. In contrast, the strain energy storage capacity of tendon collagen is between 2000 and 9000 Joule/ kg. As a result, the capacity for elastic energy storage will be greatest in muscle groups with long compliant tendons. This is given in the m. triceps surae with the achilles tendon as well as in the knee extensor muscles. Muscle and tendon elasticity contribute to the effectiveness and efficiency of human jumping. Details of the interaction between muscle contraction, elastic properties and neurol control mechanisms are not very well understood, but it is clear that muscle and tendon elasticity play an important or the important role, complementing muscle's contractile properties. Data from Komi (1990) and Schmidtbleicher et al. (1978) indicate the pre-take-off activity of the leg extensor muscles in long jumping or similar jumps. Thus the myoelectrical preconditions attribute to a combination of elastic energy storage and additional, reflexinduced, myoelectrical activity (Bosco et al.,1982) in the stretch-shortening cycle. The mechanical coupling of the muscle-tendon-complex at the very first foot contact is not well understood. Direct force measurements in the achilles tendon (Komi, 1990) show a short unloading of the tendon with high myoelectrical activity of the triceps surae muscle. An explanation of this observation is still missing. It is remarkable that over 65 % of the final take-off vertical velocity has'been achieved at maximum knee flexion (Lee et al., 1993). These results gathered on jumps of female athletes at the world student games suggest that this part of the take-off may be the most important characteristic feature of the long jump take-off. In order to promote this, the athlete must possess a strong (or stiff) leg which will resist yielding over this phase and the leg must be placed in front of the body to allow the center of mass to have the opportunity to ride over it. Therefore, the low position at touchdown is seen as a neccessary precursor for the generation of the correct position to enable this mechanical mechanisms to operate. The utilization of different concepts gave us the chance to approach to a better understanding of the long jump take-off. A combination or an evaluation of take-off leg and lead leg or arms activities respectively, could not yet be presented.

From the research of Shorten et al. (1981) it is known that the transfer of potential and kinetic energy within and between the body segments can account for over 70 % of total energy changes in a running stride. Assumming that in the long jump take-off the figure of percentage holds or is even higher, the segmental energy transfer concept reduced to mechanical energy due to gravitational and inertial forces of the segments can be appropriate for the understanding the long jump take-off. Elftman (1939a,b) in his classical study of human locomotion noted that when the rate of change of energy of a segment or the segmental mechanical power is positive, that is its energy level is increasing; the increase is due to a net inflow of energy from work done by net forces acting at the segment's joint or by net muscle moments. A positive power indicates the rate of flow of energy into the segment whereas a negative power shows the rate of outflow of energy. The typical energy flow for the successful longjump take-off will be explained using the best jump of Heike Drechsler during the World Championship in Tokyo 1991.

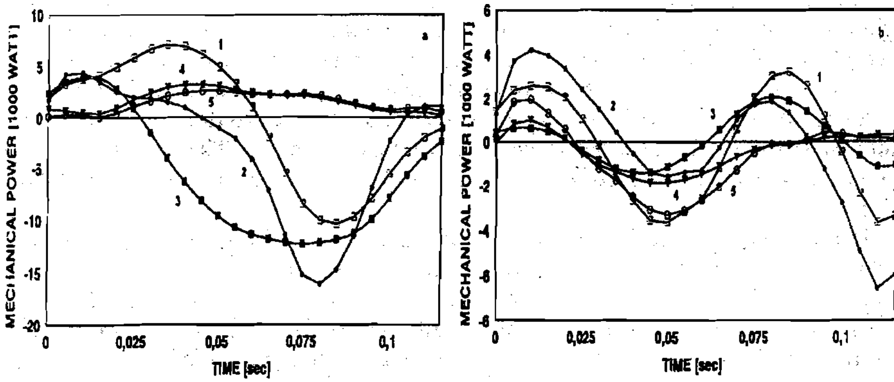

Figure 1: Mechanical power patterns of the body segments of the left (fig. 1a) and the right (fig. 1b) body sides representing a successful longjump.
(1 - thigh. 2 - shank, 3 - foot, 4 - upper arm, 5 - forearm)

The figures show the absolute value of the segmental mechanical power for the period of the take-off. Figure 1 a indicates the segments of the left side of the body and figure 1 b presents the data of the right body side. Notice that the subject is a left foot jumper. For the take-off leg two distinct phases can be identified for each segment. First an energy flow into the segment is identified with a quite different duration. While the energy flow into the supporting foot takes 30 ms, the energy flow from the thigh into the shank is 45 ms and from the trunk into the thigh about 65 ms. During the first 30 ms the take-off foot pronates and elastic energy may be transfered to the elastic structures of the medial ligaments. It can be speculatecd that some percentage of this energy can be utilized during the following period of take-off.

The lead leg power pattems indicate that energy flows first from the trunk distally for approximately 40 ms. This means that the energy outflow of the lead leg acts as an additional load against the leg extensor muscles. After this phase of distal energy outflow a period of approximately 50 ms show an energy inflow into the trunk indicated by negative power values.

The outflow-inflow mechanism is repeated in the second part of the take-off. Is is of interest that in this second outflow period the energy flow from the thigh to the shank and from the shank to the foot play the dominant role; whereas in the ultimate inflow phase the energy flow from the thigh to the trunk is dominant. This seems to indicate a suitable technical and well controlled solution of lead-leg activity.

It can be speculated that in the long jump take-off two distinct phases can be differentiated. In both phases two periods with different lead leg energy flow pattems could be found. The swinging arms do not have a major effect on the propulsion. The mechanical power pattems indicate that the left arm serves to counterbalance the body against the activity of the lead leg: while the arm on the side of the take-off leg more or less follows the lead leg power pattem.

The data underline that the closer understanding of a take-off of group TAKO I cannot be further improved with additional descriptions of CM's path, velocity or acceleration. The understanding of the interaction of both the lead leg and the support leg seems to play the most important role for further achievements in sportbiomechanics of jumping.

TAKO 2. High jump

The mechanical demand on the high jump are similar but distinguished from the longjump. In the take-off phase, the athlete exerts forces on the ground that determine the height of flight of the CM and the angular momentum that the body will have during the bar clearance. This angular momentum can be described similar to a twisting somersault. The twist makes the athlete tum the back to the bar. It is generated mainly by swinging the lead leg somewhat away from the bar. The somersault for bar clearance is the result of a forward and a lateral somersaulting component (Dapena 1991).

Similar to the group TAKO 1 the initial mechanical conditions are the horizontal CM velocity and the CM position at touchdown into the take-off.

Using the CM concept the principal considerations of a lowering of CM prior to touchdown, a shortening of the time of the ultimate flight prior to touchdown and the minimization of downward velocity are the same as in the long jump.

With the CM-concept two types of high jump strategies can be differentiated. The application of the model of partial heigths which summed up to give the total jumping height (Hay, 1985) indicate that even in elite athletes with very similar body height major differences in the CM height at take-off and the flight height, the vertical distance the CM travels after the foot leaves the ground, can be shown. The achievement of large values in the take-off height does not correlate strongly to data of the height of flight. This especially can be seen on elite level (Brüggemann, Loch 1992).

In the table, the data of H1 and H2 show variations of more than 10 % in take-off height and height of flight within the analysed sample of the World Championships finalists. Thus even in homogenous groups at an elite level quite different individual strategies seem to prevail for the achievement of maximum height.

Subject	HB	H1	H2	H3	HMAX
No.1	2.05	1.40	0.74	0.09	2.14
No.2	1.98	1.32	0.73	0.07	2.05
No.3	1.93	1.39	0.63	0.09	2.02
No.4	1.96	1.44	0.55	0.03	1.99
No.5	1.93	1.33	0.70	0.10	2.03
No.6	1.93	1.36	0.63	0.06	1.99
No.7	1.90	1.23	0.65	0.04	1.94
No.8	1.90	1.30	0.63	0.03	1.93
Mean	1.94	1.35	0.66	0.06	2.01
SD	±0.05	±0.06	±0.06	±0.03	±0.06

Table 2: Partial heights of the finalists of the 1991 World Championships in athletics. (HB: height of the bar; H1: height of center of mass at take-off; H2: vertical path of CM during flight; H3: height of bar clearence; HMAX: maximum height of CM)

The segmental contribution concept was applied to the high jump take-off by Dapena (1980a,b; 1991) who in general presented the most suitable data and biomechanical knowledge in high jumping. Dapena focussed on the arm action and reported from his data that the arms are generally accelerated upwards during the take-off and thus excert by reaction a compressive force downward on the trunk. This force is transmitted through the take-off leg to the ground. By reaction it evokes an increased force upward excerted by the ground on the athletes. This argument is valid and holds if the mechanical coupling with the ground is a stable one. The early arm action leads to a greater velocity by the end of the take-off and consequently to a higher jump. Observing the velocity-time characteristics of the lead leg and the swinging arms during take-off for successful trials a high vertical velocity occurs for these segments prior to the instant of maximum CM velocity. This observation corresponds with the acceleration patterns, which clearly show an early acceleration of the segments and an evident deceleration before the athlete leaves the ground. Individual differences of these acceleration-deceleration strategies are found, but in general these are principal trends for elite athletes (Brüggemann, Loch 1992). The data in table 3 indicate the amount of maximum vertical velocity, the vertical velocity at take-off and the differences in speed of the lead leg and the arms.

Subject	HB (m)	Lead leg (m/sec.)			Arms (m/sec.)			CM (m/sec.)
		VMAXL	VTOL	DVL	VMAXA	VTOA	DVA	VTO
No.1	2.05	6.8	2.6	-4.2	2.1	2.0	-0.1	3.81
No.2	1.98	6.3	3.8	-2.5	7.9	7.4	-0.5	3.78
N o.3	1,93	6.0	3.2	-2.8	5.1	4.5	-0.6	3.52
No.4	1.96	6.6	4.6	-2.0	5.2	3.6	-1.6	3.28
No.5	1.93	5.6	3.6	-2.0	5.5	5.1	-0.4	3.71
No.6	1.93	5.6	4.3	-1.3	7.0	5.8	-1.2	3.52
No.7	1.90	5.5	4.9	-0.6	4.6	4.2	-0.4	3.57
No.8	1.90	5.6	4.6	-1.0	7.5	7.1	-0.4	3.52
Mean	1.95	6.00	3.95	-2.05	5.61	4.96	0.65	3.59
SD	H.05'	H.48	H.74	H.74	±1.75	±1.68	H.46	±0.16

Table 3: Maximum and take-off vertical velocity of the CM, the arms and the lead leg. (HB: height of the bar; VMAXL: maximal vertical velocity of the lead leg during support; VTOL: vertical velocity of the lead leg at take-off; DVL: Difference of vertical velocity of the lead leg; VMAXA: maximum vertical velocity of the arms during support; VTOA: Vertical velocity of the arms at take-off; DVA: Difference of vertical velocity of the arms; VTO: vertical take-off velocity of CM)

The data underline the statements of an evident segmental deceleration before the foot leaves the ground.

Some authors introduced the elastic energy storage concept to proceed in the explanation of high jump take-off technique. Aura and Viitasalo (1989) indicated a high pre-take-off activity of the leg extensor muscles and an intensive eccentric muscular activity in the Fosbury Flop take-off. These data give the preconditions to discuss the energy storage concept perhaps supported by reflexinduced muscular activity.

Alexander (1990) added the elastic energy storage idea to an extended CM-concept using a simple leg model incorporating just one muscle, a knee extensor with realistic force/ velocity properties. The model ran at speed p, and set down the take-off leg at an angle 8 to the horizontal. With the muscle fully activated, the knee bent and re-extended, the athlet is thrown in the air. The vertical take-off velocity and the height of flight can be calculated. Figure 2 shows this height for different speeds ü, and angles. For a given leg angle, two very different speeds may lead to the same jump height, in which case the slower speed gives the steeper trajectory. The figure shows that the highest jumps are obtained with an approach speed of appr. 7 m/s and a leg angle of approximately 50°. It is remarkable that excellent high jumpers use appr. these values (Brüggemann, Loch,1992).

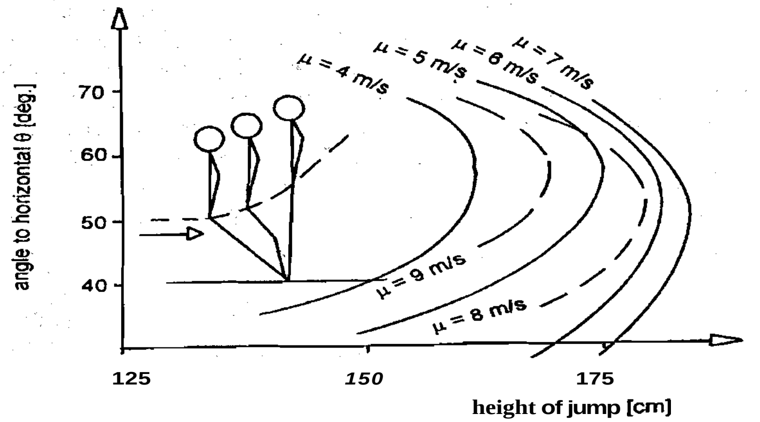

Figure 2: Heights of jumps with different angles to horizontal at touchdown and different run-up speeds (Data adapted from Alexander 1990).

In order to illuminate the interaction of the lead leg, the swinging arms and the take-off leg the energy flow concept above explained can be used.

During the first take-off period a distally energy flow of the support leg is obvious (see figure 4). Especially the energy flow from the shank into the foot in the first 60 ms after touchdown should not be underestimated. In comparison with the observation in the long jump take-off, after the curved run-up for the Fosbury Flop the amount of this outflow is extremely high. It should be transfered to the medial ligaments and other medial structures of the take-off foot. Thus a considerable source of performance optimization should be in the medial load of the foot, if the stressed structures are capable to store and re-utilize the transferred energy. From such a point of view specially designed shoes for highjump to support this strategy may be an adequate solution to optimize the take-off. From this position it is a completely different question whether, from a more preventive or load control point of view, the use of all biological structures is appropriate.

High speed recordings of the take-off foot indicate the extreme overpronation in the first quarter of the take-off. The lateral movement is combined with extremely high vertical and lateral forces. Thus the question arises if this lateral movement, which may stress the medial structures and especially the medial ligaments up to the ultimate tensile strength, is a necessary part of elastic energy storage during the Fosbury Flop take-off. First data of different elite finale jumpers indicate that differences between athletes with stable ankle trend to reutilize the stored energy more efficiently than those with unstable ankles in regard to medial-lateral control.

In the later phase of take-off one can observe an energy inflow proximally from the foot to the shank, from the shank to the thigh and from the thigh to the trunk. In technically proper or perfect jumps the power pattems of the three segments or joints respectively, occured simultaneously and precisely timed.

The lead leg shows a pronounced energy inflow proximally over the whole take-off period in most of the top athletes. In some cases this inflow is preceded by a short period of outflow. which should add the load on the leg extensor muscles and the ankle stabilizing structures of the take-off leg. Possibly there is a strategy of controlling the additonal load of these studies via the action of the lead leg. The left arm (in left leg jumpers) firstly shows an energy outflow. which - as indicated earlier - increases the load of the trunk and the take-off leg against the ground. After approximately one third of the take-off energy of the left arm is flowing-in proximally and potentiating the trunk's mechanical energy.

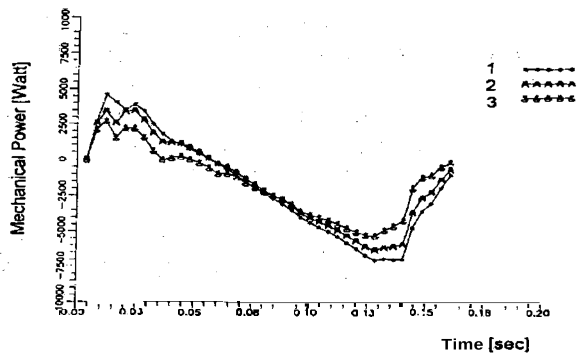

Figure 4 Energy flow (mechanical power) of the take-off leg during a successful high jump take-off.
(1 - shank ⇒ foot; 2 - thigh ⇒ shank; 3 - trunk ⇒ thigh)

Controversally the right arm first shows a proximal energy inflow into the trunk and in a later state of take-off a flow-out from the shoulder to the segment. This indicates that the two arms have - using this technique of Fosbury Flop shown by some of the world best female high jumpers - quite different patterns and functions. This is understandable and explainable when regarding the necessity of producing the twist and somersault angular momentum for bar clearance.

In conclusion, the take-off for the high jump is a complex movement in which the activity of three swinging segments are integrated into the stretch-shortening cycle of the take-off leg. The energy flow concept is able to identify different phases and mechanisms of energy transfer through the segments and can contribute to understand this specific type of human jumping.

TAKO 3. Multiple somersault take-off in diving

Only very few data and papers are available for take-off from elastic surfaces while lots of articles can be found on flights in diving. Miller (1981), Miller and Munro (1985 a,b) and Hamill et al. (1986) described the segmental contribution of linear and angular momenta during take-off. Because of the major importance of the springboard mechanics in relation to the divers movements, the TAKO 3 take-off will not be discussed in detail in this text. It is of interest that no data of the interaction between the elastic flow or the vaulting board and the gymnasts are available in the literature.

TAKO 4. Running forward somersault take-off

The running forward somersault is the classical form of frontal gymnastic take-off. However, only few sophisticated and not purely descriptive papers dealing with this manoeuver can be identified in the literature (Brüggemann, 1994). From those who used the CM-strategy we can deduce that the initial horizontal CM's speed is approximately 4 m/s and the downward velocity at touchdown -1.3 m/s (Nissinen, 1978). This relatively high downward velocity at touchdown seems to be typical for the two leg take-offs from elastic surfaces. During the take-off the athlete has to produce an optimum vertical velocity for the flight and an optimum angular momentum in order to realize the somersault rotation. In the production of angular momentum the segmental contribution concept indicates that the role the arms play for the forward rotation is often overestimated. The emphasized incorporation of arm-action does not contribute too much to the take-off angular momentum. The linear momentum contribution underlines the angular momentum findings for the vertical CM's take-off velocity. (Nissinen, 1978; Brüggemann, 1994). From these data the contribution of the arm swing seem to be of minor importance for the somersault take-off than mentioned in gymnastic textbooks and coaching manuals.

The information on leg and trunk acivities during the forward somersault take-off are extremely poor. Miller and Nissinen (1987) contributed to the understanding of the take-off mechanism by illuminating a considerable eccentric demand upon the knee and ankle extensor muscles. They added the elastic energy storage concept but did not discuss the role played by elastic surfaces. It should be mentionned that the experiment of Nissinen was executed in 1978 on a stiff force platform and therefore no elastic components of the surface could be studied.

Total mechanical energy does not change dramatically from touchdown to take-off in the running forward somersault in subjects on elite level. This statement is important because in all other take-offs discussed above a distinct loss of mechanical energy was observed. The segmental contribution to energy changes indicates the major importance of the lower extremities and the trunk for this take-off.

As in the earlier discussed take-offs the energy transfer concept can be used to explain the energy flow. It is remarkable, that a distal energy outflow from the trunk through the thigh, the shank and the foot into the elastic floor is combined with a small proximal inflow from the arms into the trunk. But this amount of power should not be overestimated considering the figures of the other segments and joints, respectively. In the recoil phase which appears very symmetrical to the compression phase, energy flow from the floor to the foot, form the foot to the shank, from the shank to the thigh and from the thigh to the trunk is obvious.

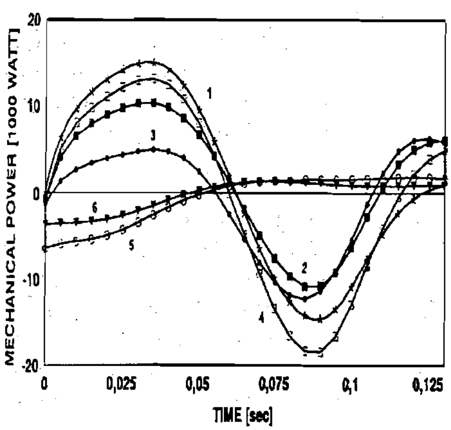

Figure 4 Mechanical power of body segments and the elastic surface during the take-off for a running forward somersault. (1 - surface; 2 - foot; 3 - shank; 4 - thigh; 5 - upper arm; 6 - forearm)

While no energy loss is observed in elite gymnasts, less skilled subjects lose a distinct percentage of total energy in the specific take-off. Top gymnasts seem to be able to adapt precisely the stiffness of their muscle-tendon system to the elasticity of the gymnastic floor.

This should be an explanation for problems, gymnasts - and especially the unexperiencedhave when the mechanical properties of a floor are changed. Therefore the take-off for the running forward somersault is not a main problem of segmental activities, but of the proper positioning of the body in regard to the ground and the stiffness regulation during and prior to rebound.

TAKO 5. Take-off for the backward somersault after a **flic-flac**

The take-off for a backward somersault after a **flic-flac** in gymnastics is unique because it is the only take-off in sports with initial angular momentum prior to take-off. The analysis of CM velocity indicates a substantial decrease of horizontal CM velocity by approximately 50 % during the take-off. The initial touch-down speed is 4.0 - 4.8 **m/s** in elite gymnasts (Briiggemann, 1983; Knoll, 1993; Hwang et al.. 1980). During the rebound the verticalvelocity of CM changes from a negative touchdown velocity (-0.5 **m/s**) to vertical take-off velocity of more than 4.1 **mls.** A large angular momentum about the transverse axis of approximately 140 kg m^2 **/s** is reduced during the take-off **bv** about 50 %.

The contribution of the body segments to CM acceleration and angular momentum was analysed by Briiggemann (1983) and Hwang et al. (1990). The legs and the trunk were found to be responsible for the majority of the total impulse over the take-off time. The highest values of the inertial force of the legs were found during the eccentric phase of leg extension activity. The acceleration time curve of the arms is quite different form that of the other segments. At touch-down the inertial force of the arms is positive and apparently plays a significant role in the stretch-shortening cycle of the lower body. The arms seem to accelerate vertically loading the leg extensors during the eccentric contraction. During the subsequent recoil and take-off drive the arms reverse their role by producing negative vertical inertial force, which results in reduced external load on the leg extensor muscles unter contraction. In the last take-off phase the arm action appears to influence the final extension of the hip, knee and ankle joints.

A similar procedure applying the segmental contribution concept was used to investigate the segmental contribution to angular momentum. Angular momentum changes in both **the trunk** and legs have similar time histories with marked initial losses that leveled out at the end of take-off. During contact the angular momentum of the arms remains relatively constant at the beginning, even with slight increase, before decreasing in the later stages of take-off. The final decreases seem to allow a differentiated modification of angular momentum of the whole body. This specific technique is used to moderate the moment of inertia for the flight, for example for the double backward layout somersault.

Briiggemann (1983) found a strong correlation **($p>0.01$)** between pre-take-off angular momentum, **CM's** velocity and the height of the flight after the take-off. Knoll (1993) reported different body positions at touchdown into the take-off in order to produce a double backward layout somersault or a double tucked or triple somersault.

Summing up we can conclude that an extended CM-concept allowed to identify the importance of the initial mechanical conditions and proved the influence of these properties to height of somersault flight and angular momentum. The segmental contribution concept contributed to a first understanding of segmental activity during take-off.

Using the mechanical energy investigation, the importance of lower body energy changes are obvious. It also demonstrates the inverse role of the **arms during** impact and recoil. The **energy flow** concept is capable to explain the mechanism and can incorporate the elastic surface in the general consideration.

The distal energy outflow from the trunk to the arms increases the load on the lower body and the elastic surface. Energy inflow from trunk into the thighs, from the thighs into the shank and from the shank into the feet and the floor are shown in the figure. In the recoil the opposite mechanism appears. Compression and depression are nearly symmetrical, indicating optimal elastic mechanical condition.

CONCLUSION

All the above findings may provide coaches and teachers with information that should not only improve their ability to effectively teach different take-off techniques. but should also improve performance by selecting appropiate training skills to optimize the specific demands of jumping.

The necessary basis to transfer scientific results into practical application and coaching practise is to build a mechanical and biomechanical understanding of jumping. Thus a purely mechanistic approach like a CM-concept cannot be appropriate.

Summing up the knowledge of jumping in sports we can state that sport biomechanics is at the beginning of understanding segmental activity and interaction.

An increase of knowledge will not be achieved by laboratory studies of vertical jumps from solid surface only. Biomechanists have to proceed to the specific jumps in sports under the specific mechanical condition of discipline under study.

With the inclusion of a load control concept which was not the topic of this presentation, biomechanical research can support practical training and coaching even better. But biomeclianics will only have a viable future in elite and leasure sports if research questions are permanently updated and specificed to the intrinsic problems of athletics and the athletes. In addition the results must be presented in a format that sport performance at all levels from elite performer to leasure sport can be improved.

This was the vision of Geoffrey DYSON when he encouraged biomechanists to cooperate with teachers and coaches for better performance.

REFERENCES

Aleshinsky, S.Y. (1986). An energy sources and fractions approach to the mechanical energy expenditure problem I-V. J. of Biomechanics,19, 287-315.

Alexander, R. McN.; Benet-Clarke, H.C (1977). Storage of elastic strain energy in muscles and other tissues. Nature, London, 265,114-117.

Alexander, R. McN. (1990). Optimization of the structure and movement of the legs of animals. J. of Biomechanics 26, Suppl. 1,1-7.

Alexander, R. McN. (1990). Optimum take-off techniques for long and high jumps. Phil. Trans. Roy. Soc. London. B. 329, 3-10.

Aura, O., Viitasalo, J.T. (1989). Biomechanical characteristics of jumping. Int. J. of Sport Biomechanics, 5, 89-98.

Bosco, C., Luthanen, P., Komi, P.V. (1975). Kinetics and kinematics of the take-off in the long jump. In: Biomechanics V. University Park Press, Baltimore,174-180.

Bosco, C., Komi, P.V. (1979). Potentiation of the mechanical behavior of the human skeletal muscle through prestetching. Acta Physiol. Scand.,106, 467-472.

Bosco, C., Komi, P.V., Ito, A. (1981). Prestretch potentiation of human skeletal muscle during ballistic movements. Acta Physiol. Scand.111,135-140.

Bosco, C., Viitaslo, J.T., Komi, P.V., Luthanen, P. (1982). Combined effect of elastic energy storage and myoelectrical potentiation during stretch-shortening cycle exercise. Acta Physiol. Scand.,114, 557-565.

Briiggemann, G.-P. (1983). Biomechanische Analyse symmetrischer Absprungbewegungen im Gerattumen (Biomechanical analysis of symmetric take-offs in gymnastics). Barlels & Wemitz, Berlin.

Brüggemann, G.P., Nixdorf, E. (1985). Geschlechtsspezifische . Unterschiede in der Technomotorik leichtathletischer SprInge (Gender specific differences in athletic jumps). In: Müller, N., Augustin, D., Hunger, B. (eds.): Frauen-Leichtathletik. SchorsVerlag, Niedemhausen,192-202.

Briiggemann, G.-P., Susanka, P. (1987). The long jump. In: Scientific Report on the Second IAAF World Championships in Athletics, Rome 1987. International Amateur Athletic Federation, London,1-54

Briiggemann, G.-P., Loch, M. (1992). The high jump: Scientific research project at the III World Championships in Athletics. New Studies in Athletics, 7, 67-72.

Briiggemann, G.-P. (1994). Biomechanics of gymnastic techniques. In: Nelson, R.C., Zatsiorsky, V.M. (eds.). Sport Biomechanics. Sport Science Review, Human Kinetic Publishers, Champaign, II, 79-120.

Cavagna,G.A., Dusman, B., Margaria, R. (1968). Positive work done by prestretched muscle. J. of Appl. Physiol., 24, 21-32.

Dapena, J. (1980a). Mechanics of tranlation in the Fosbury -flop. Med. Sci. Sports and Ex., 12, 37-44.

Dapena, J. (1980b). Mechanics of rotation in the Fosbury -flop. Med. Sci. Sports and Ex.. 12, 45-53.

Dapena, J., Chung, C.S. (1988). Vertical and radial motions of the body during the take-off phase of high jumping. Med. Sci. Sports and Ex., 20, 290-302.

Dapena, J. (1990). Biomechanics of high jumping technique. In: COOB' 92 (Ed.). Second IOC World Congress on Sport Sciences. Plaza & Janes Editores, Barcelona, 39-42

Dyson, G. (1978). The mechanics of athletics. University of London, London. Elftman, H. (1939a). Forces and energy changes in the leg during walking. American J. of Physiology,125, 339-356.

Elftman, H. (1939b). The function of muscles in locomotion. American J. of Physiology, 125, 357-366.

Elftman, H. (1940). The work done by muscles in running. American J. of Physiology, 126, 672-684.

Hamill, J., Ricard, M.D., Golden, D.M. (1986). Angular momentum in multiple rotation nontwisting platform dives. Int. J. of Sport Biomechanics, 2, 78-87.

Hay, J.G., Vaughan, C.L., Woodworth, G.G. (1981). Technique and performance: Identifying the limiting factors. In: Biomechanics VII-B, University Park Press, Baltimore, 511-520.

Hay, J.G. (1985). The biomechanics of sports techniques. Prentice-Hall International, London.

Hochmuth, G. (1982). Biomechanik sportlicher Bewegungen (Biomechanics of movements in sports). Sportverlag, Berlin.

Hwang, I. , Seo, G., Liu, Z.G. (1990). Take-off mechanics of the double backward somersault. Int. J. of Sport Biomechanics, 6,177-186.

Ingen Schenau, G.J. van, Cavagnagh, P.R. (1990). Power equations in endurance sports. J. of Biomechanics, 23, 865-882.

Ker, R.F., Bennet, M.B., Kester, R.C., Alexander, R.McN. (1987). The spring in the arch of the human foot. Nature, 325,147-149.

Knoll, K. (1993). Zum biomechanischen Wirkungsmechanismus von Flugelementen aus vorbereitenden Bewegungen und Ableitungen fur die Technik von Rondat und FlickFläck am Boden (The biomechanical chain of effect in flight elements out of preparatory movements and implications for round-off and flic-flac technique). In: Brüggemann, G.-P., Rühl, J. (eds.): Biomechanics in Gymnastics - Conference Proceedings, Strauss, Koln,115-126.

Kollath, E. (1980). Zur Kinetik des Weitsprungs unter besonderer Berücksichtigung der Gelenkbelastung (Kinetics of the long jump and mechanical load of the joints). Doctoral Dissertation, Deutsche Sporthochschule Koln.

Komi, P.V. (1990). Relevance of in vivo force measurements in human biomechanics. J. of Biomechanics. 23, Suppl.1, 23-34.

Lees, A., Fowler, N., Derby, D. (1993). A biomechanical analysis of the last stride, touchdown and take-off characterists of the women's long jump. J. of Sports Sciences, 11, 303-314.

Miller, D.I., East, D.J. (1975). Kinematic and kinetic correlates of vertical jumping in woman. In: Biomechanics V-B, University Park Press, Baltimore, 65-72

Miller, D.I. (1976). A biomechanical analysis of the contribution of the trunk to standing vertical jump take-offs.In: Broekhoff, J. (ed.): Physical Education, Sports and the Science. OR: Microform Publications, Eugene, 354-376.

Miller, D.I. (1981). Body segment contributions of female athletes to translation and rotational requirements of non-twisting springboard dive take-offs. In: Borms, J., Hebbelink, M., Venerando, A. (eds.): The Female Athlete. Karger, Basel, 206-215.

Miller, D.I., Munro, C.F. (1985 a). Greg Louganis' springboard take-off: I: temporal and joint position analysis. Int. J. of Sport Biomechanics,1, 209-220.
Miller, D.I., Munro, C.F. (1985 b). Greg Louganis' springboard take-off: II: Linear and angular momentum considerations. Int. J. of Sport Biomechanics,1, 288-307.
Miller, D.I., Nissinen, M.A. (1987). Critical examination of ground reaction force in the running forward somersault. Int. J. of Sport Biomechanics, 3,189-206.
Nissinen, M.A. (1978). Kinematic and kinetic analysis of the hurdle and support phase of a running forward somersault. Master Thesis, University of Washington.
Ridka-Drdacka, E. (1986). A mechanical model of the long jump and itüs application to a technique of preparatory and take-off phases. Int. J. of Sport Biomechanics, 2,289- 300.
Schmidtbleicher, D., Dietz, V., Noth, J. Antoni, M. (1978). Auftreten und funktionelle Bedeutung des Muskeldehnungsreflexes bei Lauf- und Sprintbewegungen (Occurence and function of reflex induced muscle activity in running and sprinting). Leistungssport. 8, 480-490.
Shorten, M.R., Wootton, S.A., Williams, C. (1981). Mechanical energy changes and oxygen cost of running. Engng. Med.,10, 213-217.
Takei, Y. (1990). Techniques used by elite women gymnasts performing the handspring vault at the 1987 Pan American Games. Int. J. of Sport Biomechanics, 5,1-25.
Winter, D.A. (1978). Calculation and interpretation of mechanical energy of movement.
Exercise and Sport Science Reviews, 6,183-201.