A BIOMECHANICAL SCIENTIFIC SUPPORT PROGRAM FOR HIGH JUMPERS

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THE ELITE ATHLETE PROJECT

In 1981 the United States Olympic Committee (USOC) and the national governing bodies for several sports started a biomechanics research program that sought to improve the performance of elite athletes in the United States. Initially known as the Elite Athlete Project, it had two separate but complementary objectives: to generate new scientific information on sport biomechanics (basic research), and to provide direct advice for the top American athletes (applied research). The USOC has its own biomechanics laboratory in Colorado Springs, but the project was too extensive for a single laboratory, so it was distributed among specialized research groups across the country. Several laboratories had been conducting research in sport biomechanics prior to 1981, but usually with little or no contact with the USOC nor with other sport governing bodies. The Elite Athlete Project would now help to fund those research efforts, and would also promote closer ties between the researchers and elite athletes.

RESEARCH ON HIGH JUMPING

The high jump event of track and field was assigned to our laboratory, and we have been collaborating with the USOC and with the national governing body for track and field athletics (USA Track & Field or USATF, formerly known as The Athletics Congress). In our basic research we seek to further our knowledge of high jumping technique; in our applied research we use the information obtained in the basic research to try to improve the techniques of individual high jumpers. The applied research provides us with a large data base of analyzed jumps, and also raises questions that we try to answer later with the basic research. Thus, each line of research provides information that is useful for the other.

OVERVIEW OF THE APPLIED RESEARCH

For the applied research, we usually film a major high jump competition in June/July. The films are digitized later in the summer, the data are interpreted in October/November, and written reports and instructional videotapes are sent to the athletes in December. A meeting with the athletes and coaches is usually scheduled for early January to discuss results and answer questions. Early on, we weighed the advantages of a quick feedback against the disadvantages of a more hurried and less complete analysis, and opted to be thorough rather than quick. The idea is to provide information that will help the athletes to make technique changes from one season to the next, rather than from one competition to the next.

REPORTS AND VIDEOTAPES

Each written report gives a detailed biomechanical explanation of standard high jumping technique, followed by an analysis of the technique of each athlete and advice for the correction of defects. The videotape uses computer animation, and is in essence a simplified version of the written report. The animations show views of each jump from various directions.

FILM ANALYSIS

During the competitions, the athletes are filmed simultaneously with two 16-mm motion-picture cameras shooting at 50 fr/s. The DLT method (Abdel-Aziz and Karara, 1971; Walton, 1981) is used to obtain three-dimensional coordinates of 21 body landmarks in the last two steps of the run-up, the takeoff and the bar clearance. The coordinates are used to calculate diverse mechanical parameters of the jumps, and several motion sequences are produced for each jump using computer graphics.

EVALUATION OF HIGH JUMPING TECHNIQUE

In the reports, we evaluate the techniques of the athletes, and give advice for the correction of problems (Dapena *et al.*, 1995). The rationale used for the technique evaluations stems from a comprehensive interpretation of the Fosbury-flop style of high jumping based on the research of Dyatchkov (1968) and Ozolin (1973), on the basic research of our group (Dapena, 1980a, 1980b, 1987, 1995; Dapena *et al.*, 1988, 1990), and on the experience accumulated through the analysis of high jumpers at our laboratory in the course of previous applied research work. The rest of this paper will explain the rationale followed to judge the technique of each athlete.

PARTS OF THE JUMP

We divide the high jump into three phases: the run-up, the takeoff, and the flight or bar clearance. The purpose of the run-up is to set the appropriate conditions for the start of the takeoff phase, which is the most important part of the jump. During the takeoff phase, the athlete exerts forces on the ground which determine the maximum height that the center of mass (c.m.) will reach and the angular momentum that the body will have during the bar clearance. Once in the air, the control capabilities of the athlete are limited: Only internal compensatory movements are possible (e.g., one part of the body can be lifted by lowering another part; or it can be made to rotate faster by making another part slow down its rotation). Most bar clearance problems originate in the run-up or takeoff.

GENERAL CHARACTERISTICS OF THE RUN-UP

In experienced high jumpers, the typical run-up is about 10 steps long. The first part usually follows a straight line perpendicular to the plane of the standards; the last four or five steps follow a curve. One of the main purposes of the curve is to make the jumper lean away from the bar at the start of the takeoff phase. The faster the run or the tighter the curve, the greater the lean toward the center of the curve. In the early part of the run-up the speed and the length of the steps should increase gradually. After a few steps, the high jumper should be running fast, with long, relaxed steps, similar to those of a 400-meter or 800-meter runner. In the last two or three steps the athlete should gradually lower the hips; this should be done with little or no loss of running speed.

HORIZONTAL VELOCITY AND C.M. HEIGHT AT THE END OF THE RUN-UP

The takeoff phase is the time period between the instant when the takeoff foot first touches the ground (touchdown) and the instant when it leaves the ground (takeoff). During the takeoff phase, the takeoff leg pushes down on the ground. In reaction, the ground pushes up on the body with an equal and opposite force which changes the vertical velocity of the c.m. from a value that is initially near zero to a large upward vertical velocity. The vertical velocity at the end of the takeoff determines how high the c.m. will go after the foot leaves the ground. Therefore, it is very important for the result of the jump. To maximize vertical velocity at the end of the takeoff, the product of the vertical force exerted by the athlete on the ground and the time during which it is exerted should be as large as possible. This can be achieved by exerting a large vertical force while the c.m. travels through a long vertical range of motion. A fast run-up can help the athlete to make a larger vertical force on the ground. This can happen in the following way: When the athlete plants the takeoff leg ahead of the body at the end of the run-up, the knee and hip extensor muscles resist against the flexion of the leg, but the forward momentum of the jumper forces the leg to flex anyway. This process stretches the muscles, and allows them to exert larger tensions. In this way, a fast horizontal speed at the end of the run-up (v_{H1}) helps to increase the horizontal *and vertical* forces exerted on the ground during the takeoff phase. (For a more extended discussion of the process, see Dapena and Chung, 1988.) To maximize the vertical range of motion of the c.m. during the takeoff phase, it is necessary for the c.m. to be low at the start of the takeoff phase and high at the end of it. The c.m. of most high jumpers is reasonably high at the end of the takeoff, but it is difficult to have the c.m. in a low position at the start of the takeoff phase. This is because it requires the body to be supported by a deeply flexed non-takeoff leg in the next-to-last step of the run-up, which requires a very strong non-takeoff leg; it is also difficult to learn the neuromuscular patterns that will permit the athlete to pass over the deeply flexed non-takeoff leg without losing speed. We measure the c.m. height at the instant that the takeoff foot is planted on the ground to start the takeoff phase (h_{TD}). It is expressed in meters, and also as a percent of the standing height of the athlete; the percent values are more meaningful for comparisons among athletes. It is possible to use a run-up that is fast and low in the last steps, but this requires considerable effort and training. An appendix of the report describes some exercises that can help high jumpers to lower the c.m. in the last steps of the run-up without losing speed. Once an athlete has learned how to run fast and low, a new problem could occur: The athlete could actually be too fast and too low. If the takeoff leg is not strong enough, it will be forced to flex excessively during the takeoff phase, and then it may not be able to make a forceful extension in the final part of the takeoff phase. In other words, the takeoff leg may suffer partial or complete buckling (collapse) under the stress, and the result will be a poor (or possibly aborted) jump. Therefore, it is important to find the optimum combination of run-up speed and c.m. height for each high jumper. We will now see how this can be done. The report shows a plot of h_{TD} (ordinates) versus v_{H1} (abscissae) for the analyzed athletes. This kind of graph allows us to visualize simultaneously how fast and how low an athlete was at the end of the run-up. For instance, a point in the lower left part of the graph would indicate a jump with a slow run-up and a low c.m. position at the end of the run-up. Let us first consider what would happen if all the athletes in the graph had similar dynamic strength in the takeoff leg. In such case, the athletes in the upper left part of the graph would be far from their limit for buckling, the athletes in the lower right part of the graph would be nearest to buckling, and the athletes in the center, lower left and upper right parts of the graph would be somewhere in between with respect to buckling. Therefore, if all the athletes shown in the graph had similar dynamic strength, we would recommend the athletes in the upper left part of the graph to run faster and lower. The athletes in the center, lower left and upper right parts of the graph would also be advised to experiment with faster and lower run-ups, possibly emphasizing "faster" for the jumpers in the lower left part of the graph, and "lower" for the jumpers in the upper right part of the graph. The athletes in the lower right part of the graph would be cautioned against the use of much faster and/or lower run-ups than their present ones, because they would already be closer to buckling than the others. The procedure just described would make sense if all jumpers had similar dynamic strength in the takeoff leg. However, this is unlikely: Some high jumpers will be stronger than others. Therefore, it is possible that an athlete in the upper left part of the graph might be weak, and therefore close to buckling, while an athlete farther down and to the right in the graph might be stronger, and actually farther from buckling. So the optimum combination of run-up speed and c.m. height will be different for different high jumpers. High jumpers with greater dynamic strength in the takeoff leg will be able to use faster and lower run-ups without buckling during the takeoff phase. However, it is not easy to measure the "dynamic strength" of a high jumper's takeoff leg; the personal record of an athlete in a squat lift or in a vertical jump-and-reach test are not good indicators. This is because these tests do not duplicate closely enough the conditions of the high jump takeoff. Therefore, we use instead the vertical velocity of the high jumper at the end of the takeoff (which is measured in the analysis) as a rough indicator of the dynamic strength of the takeoff leg. In other words, we use the capacity of a high jumper to generate lift in a high jump as a rough indicator of the athlete's dynamic strength. To help us estimate the optimum horizontal speed at the end of the run-up for each individual high jumper, we use statistical information taken from previous analyses of elite high jumpers (Dapena *et al.*, 1990). Horizontal speed at the end of the run-up (ordinates) is plotted versus vertical velocity at takeoff (abscissae). The strongest high jumpers are those able to generate more lift, and they are to the right in the graph; the weaker jumpers are to the left. A regression line shows a positive trend in the statistical data. This graph agrees with expectations: The more powerful jumpers are able to get more lift, and they can also handle faster run-ups without buckling. So, what is the optimum run-up speed for a given high jumper? It seems safe to assume that high jumpers will rarely run so fast that the takeoff leg will buckle. This is because a fast run-up requires intense, conscious effort, and if the athlete feels that the leg has buckled in one jump, an easier (slower) run-up will be used in further jumps. Since partial buckling will begin to occur at run-up speeds immediately faster than the optimum, this means that very few high jumpers will use regularly run-ups that are faster than their optimum. We should expect a larger number of high jumpers to use run-up speeds that are slower than their optimum. This is because quite a few high jumpers have not learned how to run fast enough in the run-up. Therefore, the regression line which marks the average trend in the graph probably represents speeds that are somewhat slower than the optimum. In sum, although the precise value of the optimum run-up speed for any given value of the vertical velocity at takeoff is not known, it is probably faster than the value indicated by the regression line. Therefore, athletes near the regression line or below it were probably running too slowly at the end of the run-up. A similar rationale can be followed with a plot of c.m. height at touchdown (ordinates) versus vertical velocity at takeoff (abscissae). Again, the most powerful high jumpers are to the right in the graph, and the weaker jumpers are to the left. A regression line shows a negative trend in the statistical data. Although the relationship is more noisy than in the previous graph, it also agrees with our general expectations: The stronger jumpers are able to be lower at the end of the run-up without buckling. Jumpers on the regression line or above it will have inferior techniques, and the optimum will be somewhere below the regression line. When the two graphs just described are used as diagnostic tools, it is necessary to take into consideration the information from both graphs. For instance, if a given athlete is near both regression lines, or below the regression line in the first graph and above it in the second, we should presume that this athlete is not near the buckling point. Therefore the athlete should be advised to increase the run-up speed and/or to run with lower hips at the end of the run-up. However, if an athlete is slightly below the regression line in the first graph, but markedly below it in the second, the case is dif ferent. Since the c.m. was very low during the run-up, the athlete may have been near the buckling point, even though the run-up speed was not very fast. In that case, it would not be appropriate to advise an increase in run-up speed, even if the athlete was somewhat slower than expected. A word of caution: The use of a faster and/or lower run-up will put a greater stress on the takeoff leg, and although it may lead to higher jumps it may also increase the risk of injury if the leg is not strong enough. Therefore, athletes are warned to be careful in the adoption of a faster and/or lower run-up. If the desired change is very large, it is advisable to make it gradually, over a period of time, and in all cases it is wise to strengthen the takeoff leg.

VERTICAL VELOCITY OF THE C.M. AT THE START OF THE TAKEOFF PHASE

The vertical velocity at the end of the takeoff phase, which is of crucial importance for the height of the jump, is determined by the vertical velocity at the start of the takeoff phase and by the change that takes place in its value during the takeoff phase. In normal high jumping, at the end of the run-up (that is, at the start of the takeoff phase) the athlete is moving fast forward, and also slightly downward. In other words, the vertical velocity at the start of the takeoff phase usually has a small negative value. It is evident that for a given change in the vertical velocity during the takeoff phase, the athlete with the smallest amount of negative vertical velocity at touchdown will jump the highest, so this is a technique advantage. In each step of the run-up the c.m. normally moves up slightly as the athlete takes off from the ground, reaches a maximum height, and then drops down again before the athlete plants the next foot on the ground. In the last step of the run-up, if the takeoff foot is planted on the ground early, the takeoff phase will start before the c.m. acquires too much downward vertical velocity. To achieve this, the athlete has to try to make the last two foot contacts with the ground very quickly one after the other. In other words, the tempo of the last two foot contacts should be very fast. If the last step is very long, this could be associated with a late planting of the takeoff foot, and therefore with a large negative vertical velocity at touchdown. Another factor that affects the vertical velocity at the start of the takeoff phase is the way in which the c.m. is lowered in the final part of the run-up. High jumpers can be classified into three groups, according to the way in which they lower the c.m. Many athletes lower their c.m. early (2 or 3 steps before the takeoff), and then they move more or less flat in the last step. These athletes typically have a moderate amount of downward vertical velocity at the start of the takeoff phase. The second group of athletes keep their hips high until almost the very end of the run-up, and then they lower the c.m. in the last step. These athletes tend to have a large negative vertical velocity at the start of the takeof phase. The third group of athletes lower the c.m. in the same way as the first group, but then they raise it again quite a bit as the non-takeoff leg pushes off into the last step. These athletes typically have a very small amount of downward vertical velocity at the start of the takeoff phase, and this is good, but they also waste part of their previous lowering of the c.m. The first and the third techniques have both advantages and disadvantages, but the second technique seems to be less sound than the other two, because of the large downward vertical velocity that it produces at the start of the takeoff phase.

ORIENTATION OF THE TAKEOFF FOOT; RISK OF ANKLE AND FOOT INJURIES

In a view from overhead, at the end of the run-up the high jumper's c.m. is moving at an oblique angle with respect to the bar. During the takeoff phase, the athlete pushes on the ground vertically downward, and also horizontally. The horizontal force component points forward, almost in line with the final direction of the run-up, but usually it is also deviated slightly toward the landing pit. Most high jumpers plant the takeoff foot on the ground with its longitudinal axis pointing in a direction that is not aligned with the final direction of the run-up nor with the horizontal force that the athlete is about to make on the ground; it is more parallel to the bar than either one of them. Since the horizontal reaction force that the foot receives from the ground is not aligned with the longitudinal axis of the foot, it tends to make the foot pronate. This stretches the medial side of the ankle joint, and produces compression in the lateral side. Severe pronation can lead to ankle injury. It also makes the foot be supported less by its outside edge, and more by the longitudinal arch of the foot on the medial side. This can lead to injury of the foot itself. Pronation occurs in the takeoffs of many high jumpers. However, it is difficult to see without a very magnified image of the foot, and therefore it is not clearly visible in our films. In an efort to diagnose the risk of ankle and foot injury, for every jumper we measure angles e_1 (between the longitudinal axis of the foot and the bar), e_2 (between the longitudinal axis of the foot and the final direction of the run-up) and e_3 (between the longitudinal axis of the foot and the horizontal force). For the diagnosis of the risk of injury, e_3 is the most important angle. Although the safety limit is not known with certainty at this time, anecdotal evidence suggests that e_3 values smaller than 20 degrees are reasonably safe, that e_3 values between 20 and 25 degrees are somewhat risky, and that e_3 values larger than 25 degrees are dangerous.

TRUNK LEAN

The trunk normally has a backward lean at the start of the takeoff phase. Then it rotates forward, and by the end of the takeoff it is usually close to the vertical. Due to the curved run-up, the trunk normally has also a lateral lean toward the center of the curve at the start of the takeoff phase. During the takeoff phase it rotates toward the right (toward the left in athletes that take off from the right foot), and by the end of the takeoff it is usually somewhat beyond the vertical; up to 10 degrees beyond the vertical may be considered normal. These backward/forward and left/right rotations during the takeoff phase are linked with the generation of the angular momentum needed for the execution of an appropriate bar clearance (see below). To maximize the vertical range of motion of the c.m. during the takeoff phase, the athlete needs to be near the vertical at the end of the takeoff. Since the athlete has to rotate forward and toward the right during the takeoff phase, but also needs to be near the vertical at the end of the takeoff, the athlete needs to have the right amount of lean backward and toward the left at the beginning of the takeoff phase. The reports evaluate the backward/forward and left/right angles of lean of the trunk at the start and at the end of the takeoff phase.

ARM AND LEAD LEG ACTIONS

The actions of the arms and of the lead leg during the takeoff phase are important for the outcome of the jump. By throwing these free limbs upward, the athlete slows down the upward motion of the trunk, and therefore puts the muscles of the takeoff leg in slower concentric conditions. This helps to increase the vertical force exerted on the ground and therefore also the ground's reaction to it. In this way while the acceleration of the trunk is reduced, the acceleration of the body as a whole is increased. The result is a greater vertical velocity of the c.m. at the end of the takeoff, and consequently a higher jump. There is no perfect way to measure how active the arms and the lead leg are during the takeoff phase of a high jump. In our reports we have progressively sought to improve our measurement of this important technique factor. In the latest reports, arm activeness was measured as the maximum vertical range of motion of the c.m. of each arm during the takeoff phase (relative to the upper end of the trunk), multiplied by the fraction of the whole body mass that corresponds to the arm, and divided by the standing height of the subject. The activeness of the lead leg was similarly measured as the maximum vertical range of motion of the c.m. of the lead leg during the takeoff phase (relative to the lower end of the trunk), multiplied by the fraction of the whole body mass that corresponds to the lead leg, and divided by the standing height of the subject. So the activeness of each free limb was expressed as the number of millimeters contributed by the limb motion to the lifting of the c.m. of the whole body during the takeoff phase, per meter of standing height. Defined in this way, the activeness measure of each free limb considers the average vertical force made on it, the time during which this force is exerted, and the standing height of the jumper. It allows comparisons among jumpers, and also the direct comparison of the lead leg action with the arm actions. For a good arm action, both arms should swing violently forward and up during the takeoff phase. The arms should not be too flexed at the elbow during the swing; a good elbow angle seems to be somewhere between full extension and 90 degrees of flexion.

Some high jumpers (including many women) fail to prepare their arms in the last steps of the run-up, and at the beginning of the takeoff phase the arm nearest to the bar is ahead of the body instead of behind it. From this position the arm is not able to swing strongly forward and upward during the takeoff, so these jumpers usually end up with small arm activeness values for the arm nearest to the bar. These athletes should learn to bring both arms back in the final one or two steps of the run-up, so that both arms can later swing hard forward and up during the takeoff phase. If a jumper is unable to prepare the arms for a double-arm action, the forward arm should at least be in a low position at the start of the takeoff phase. That way, it can be thrown upward during the takeoff, although usually not quite as hard as with a double-arm action.

HEIGHT AND VERTICAL VELOCITY OF THE C.M. AT THE END OF THE TAKEOFF

The peak height that the c.m. will reach over the bar is completely determined by the height and the vertical velocity of the c.m. at the end of the takeoff. At the instant that the takeoff foot loses contact with the ground, the c.m. of a high jumper is usually at a height somewhere between 68% and 73% of the standing height of the athlete. This means that tall high jumpers have an advantage: Their centers of mass will generally be higher at the instant that they leave the ground. The vertical velocity of the c.m. at the end of the takeoff determines how much higher the c.m. will travel beyond the takeoff height after the athlete leaves the ground.

CLEARANCE HEIGHT; EFFECTIVENESS OF THE BAR CLEARANCE

The true value of a high jump generally is not known: If the bar is knocked down, the jump is ruled a foul and the athlete gets zero credit, even though a hypothetical bar set at a lower height would have been cleared successfully; if the bar stays up, the athlete is credited with the height at which the bar was set, even if the jumper had room to spare over it. With computer modeling and graphics, we can estimate the maximum height that an athlete would have been able to clear cleanly without touching the bar in a given jump, regardless of whether the actual jump was officially a valid clearance or a miss. Using curvilinear interpolation between successive frames of the jump, we can saturate a computer-made drawing with interpolated images. This reveals the maximum height of the clear space below the body, i.e., the maximum height that could have been cleared cleanly in the jump. It is called the clearance height, and it indicates the true value of the jump. The clearance height is usually lower than the peak height of the c.m., and the difference between them reflects the effectiveness of the bar clearance; larger negative numbers indicate less effective bar clearances. The most usual reasons for an ineffective bar clearance are: taking off too close or too far from the bar, insufficient somersaulting angular momentum, insufficient twist rotation, poor arching, and bad timing of the arching/unarching process. These aspects of high jumping technique will be discussed next.

TAKEOFF DISTANCE

The distance between the toe of the takeoff foot and the plane of the bar and the standards is called the "takeoff distance", and it is important because it affects the position of the peak of the jump relative to the bar: If an athlete takes off too far from the bar, the c.m. will reach its maximum height before crossing the plane of the standards, and the jumper will probably fall on the bar; if the athlete takes off too close to the bar, there will be a large risk of hitting the bar while the c.m. is on the way up to its maximum height. Different athletes usually need different takeoff distances. The optimum takeoff distance for each athlete is the one that will make the c.m. reach its maximum height more or less directly over the bar, and it will depend primarily on the final direction of the run-up and on the amount of residual horizontal velocity of the athlete after the completion of the takeoff. In general, athletes that travel more perpendicular to the bar in the final steps of the run-up will also travel more perpendicular to the bar after the completion of the takeoff, and they will need to take off farther from the bar. Athletes that run faster in the final steps of the run-up will generally also have more horizontal velocity left after takeoff; thus, they will travel through larger horizontal distances after the completion of the takeoff than slower jumpers, and they will also need to take off farther from the bar.

ANGULAR MOMENTUM

The bar clearance technique of a Fosbury-flop can be described roughly as a twisting somersault, and high jumpers need appropriate angular momentum to make the necessary rotations in the air. The angular momentum is obtained during the takeoff phase, through the reactions to the forces that the takeoff foot makes on the ground. It cannot be changed after the athlete leaves the ground.

THE TWIST ROTATION

To a great extent, the twist rotation (which makes the athlete turn the back to the bar during the ascending part of the flight path) is generated by swinging the lead leg up and somewhat away from the bar during the takeoff, and also by actively turning the shoulders and arms during the takeoff in the desired direction of the twist. These actions create angular momentum about a vertical axis. It is called the twisting angular momentum. Most high jumpers have no difficulty obtaining an appropriate amount of twisting angular momentum. (However, we will see later that the actions that the athlete makes in the air, as well as other factors, can also affect the twist orientation of the high jumper at the peak of the jump.)

THE SOMERSAULT ROTATION: FORWARD COMPONENT

The somersault rotation, which will make the shoulders go down while the knees go up, results from two components: a forward somersaulting component and a lateral somersaulting component. During the takeoff phase, the athlete produces angular momentum about a horizontal axis perpendicular to the final direction of the run-up. This forward rotation is similar to the one produced when a person hops off from a moving bus facing the direction of motion of the bus: After the feet hit the ground, the tendency is to rotate forward and fall flat on one's face. It can be described as angular momentum produced by the checking of a linear motion. The tilt angles of the trunk at the start and at the end of the takeoff phase (see above) are statistically related to the angular momentum obtained by the athlete. Large changes in the trunk angle from a backward-tilted position toward the vertical during the takeoff phase are associated with a larger amount of forward somersaulting angular momentum. This makes sense, because athletes with a large amount of forward somersaulting angular momentum at the end of the takeoff should also be expected to have a large amount of it already during the takeoff phase, and this should contribute to a greater forward rotation of the body in general and of the trunk during the takeoff phase. The forward somersaulting angular momentum can also be affected by the actions of the arms and of the lead leg. Wide swings of the arms and of the lead leg during the takeoff can help the athlete to jump higher (see above). However, in a view from the side they also imply backward rotations of these limbs, which can reduce the total forward somersaulting angular momentum of the body. To diminish this problem, some high jumpers twist the upper trunk away from the bar in the last step of the run-up, and then swing the arms diagonally forward and away from the bar during the takeoff phase. Since this diagonal arm swing is not a perfectly backward rotation, it interferes less with the generation of forward somersaulting angular momentum.

THE SOMERSAULT ROTATION: LATERAL COMPONENT

During the takeoff phase, angular momentum is also produced about a horizontal axis in line with the final direction of the run-up. In a rear view of an athlete that takes off from the left leg, this angular momentum component appears as a clockwise rotation. If a jumper made use of a straight run-up, in a rear view the athlete would be upright at touchdown, and leaning toward the right at the end of the takeoff. Since a leaning position would result in a lower height of the c.m. at the end of the takeoff, the production of angular momentum would thus cause a reduction in the vertical range of motion of the c.m. during the takeoff phase. However, if the athlete uses a curved run-up, the initial lean of the athlete to the left at the end of the approach run may allow the athlete to be upright at the end of the takeoff. The final upright position contributes to a higher c.m. position at the end of the takeoff, and the initial lateral tilt contributes to a lower c.m. position at the start of the takeoff phase. Therefore the curved run-up, together with the generation of lateral somersaulting angular momentum, contributes to increase the vertical range of motion of the c.m. during the takeoff phase, and thus permits greater lift than if a straight run-up were used. There is some statistical association between large changes in the left/right tilt angle of the trunk during the takeoff phase and large amounts of lateral somersaulting angular momentum at the end of the takeoff. This makes sense, because athletes with a large amount of lateral somersaulting angular momentum at the end of the takeoff should also be expected to have a large amount of it already during the takeoff phase, and this should contribute to a greater rotation of the trunk during the takeoff phase, from its initial lateral tilt to the vertical. In a view from the back, a diagonal arm swing (see above) is associated with a clockwise motion of the arms, and therefore it contributes to the generation of lateral somersaulting angular momentum.

THE SOMERSAULT ROTATION: RESULTANT

High jumpers usually have more lateral than forward somersaulting angular momentum. The sum of these two angular momentum components adds up to the required total (or "resultant") somersaulting angular momentum. In general, athletes with more angular momentum tend to rotate faster. Female high jumpers tend to acquire more angular momentum than the men. This is because the women don't jump quite as high, and therefore they need to rotate faster to compensate for the shorter time that they have available between takeoff and the peak of the jump.

ADJUSTMENTS IN THE AIR

After the takeoff is completed, the c.m. path is totally determined. However, this does not mean that the paths of all body parts are determined. It is possible to move one part of the body in one direction if other parts are moved in the opposite direction. Using this principle, after the shoulders pass over the bar the high jumper can raise the hips by lowering the head and the legs. For a given c.m. position, the farther the head and the legs are lowered, the higher the hips will be lifted. This is the reason for the arched position on top of the bar. To a great extent, the rotation of the high jumper in the air is also determined once the takeoff is completed, because the angular momentum cannot be changed after takeoff. However, some alterations of the rotation are still possible. By slowing down the rotations of some body parts, other body parts will speed up as a compensation. The principles of action and reaction just described for translation and rotation result in the typical arching and un-arching actions of high jumpers over the bar: The athlete needs to arch in order to lift the hips, and then to un-arch in order to speed up the rotation of the legs. As the body un-arches, the legs go up, but the hips go down. Therefore, timing is critical: If the body un-arches too late, the calves will knock the bar down; if the body un-arches too early, the athlete will "sit" on the bar and will also knock it down. Rotation can also be changed by altering the moment of inertia. A reduced moment of inertia will increase the angular velocity. If an athlete maintains a small moment of inertia about an axis parallel to the bar (for instance, by keeping the knees very flexed), the somersault rotation will be faster, which will generally help to produce a better bar clearance.

RECENT FINDINGS ABOUT THE TWIST ROTATION

It was pointed out earlier that the twist rotation is produced to a great extent by the twisting component of angular momentum, but other factors can also affect the twist rotation. Recent basic research work at our laboratory has shown that only about half of the twist rotation is produced through angular momentum; the other half is produced through rotational action-and-reaction about the longitudinal axis of the body ("catting") which does not require angular momentum. Some jumpers use the twisting angular momentum more; others use catting more. If not enough twisting angular momentum is generated during the takeoff phase, or if the athlete does not do enough catting in the air, the athlete will not twist enough, which will make the body be in a tilted position at the peak of the jump, with the hip of the lead leg lower than the hip of the takeoff leg. This will put the hip of the right leg (i.e., the low hip) in danger of hitting the bar. This problem can also occur through other mechanisms: If an athlete is tilted too far backward or toward the right at the end of the takeoff, or if the lead leg is lowered too soon after takeoff, or if the forward component of somersaulting angular momentum is much larger than the lateral component, the athlete will also tend to be undertwisted at the peak of the jump. We understand well now the cause-effect mechanisms involved, but they are too complex to discuss here. When this kind of problem occurs, it is necessary to check the cause of the problem in each individual case, and then decide the easiest way to correct it.

CONTROL OF AIRBORNE MOVEMENTS; COMPUTER SIMULATION

We have seen that the c.m. path and the angular momentum of a high jumper are determined by the time the athlete leaves the ground. We have also seen that in spite of these restrictions, the athlete still has some control over the movements of the body during the airborne phase. Sometimes it is easy to predict in rough general terms how the motions of certain body parts during the airborne phase will affect the motions of the rest of the body, but it is difficult to judge through simple "eyeballing" whether the *amounts* of motion will be sufficient to achieve the desired results. Other times, particularly in complex three-dimensional airborne motions such as those involved in high jumping, it is not even possible to predict the *kinds* of motions that will be produced by actions of other body parts, much less their amounts. To help solve this problem, we often make use of computer simulation (Dapena, 1981). In this process, we give the computer the path of the c.m. and the angular momentum of the body from a specific jump that was studied previously using film analysis. We also give the computer the patterns of motion (angles) of all body segments relative to the trunk during the entire airborne phase. A computer program then calculates how the trunk has to move during the airborne phase to maintain the path of the c.m. and the angular momentum of the whole body the same as in the original jump. If we input the original patterns of motion of the segments (that is, the patterns of motion that occurred in the original jump), the computer generates a jump that is practically identical to the original jump. But if we input altered patterns of motion of the segments, the computer will generate an altered jump. This is the jump that would have been produced if the athlete had used the same run-up and takeoff as in the original jump, but then decided to change the motions of the limbs after taking off from the ground. Once the computer has generated the simulated jump, this jump can be shown using graphic representations just like any other jump. The computer simulation method just described is used to test for viable alternatives in the airborne actions of the high jumpers.

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