Biomechanics of Volleyball

1. Jumping and landing

In order to serve, set, spike or block the ball as high as possible, the jumping ability is a key factor in indoor and beach volleyball. A great jumping height allows the server to play the ball with a flatter initial projection angle, the setter to decrease the time between set and attack, the attacker to spike over the block and the blocker to overreach the net with the arms. Individual muscle properties, movement conditions and jumping technique determine the height of a jump. Following a jump landing is inevitable and the way athletes land will influence the stress in their joints. Therefore, landing techniques are crucial regarding injury prevention.

a. The neuromechanics of jumping

There is a deterministic relationship between the velocity of the centre of mass (CoM) at take-off (v_{TO}) and its increase in height during a jump (Equ. (i)). Thus, athletes intend to accelerate their centre of mass to maximize take-off velocity. According to Newton's law of motion (Equ. (ii)), the necessary acceleration (a) is proportional to the sum of the applying forces (F_i). During a jump the forces acting on the body are at one hand the weight of the athlete and on the other hand the forces developed by the muscles that are transferred to the ground. While the constant weight force is acting downwards, athletes extend their legs to produce force that accelerates the CoM upwards. The more force they are able to apply on the ground until take-off (i.e. the greater the applied impulse), the higher they accelerate their centre of mass which results in a higher take-off velocity, leading to greater jumping heights.

i) $$h = \frac{v_{TO}^2}{2 \cdot g}$$ ii) $$\sum F_i = m \cdot a$$

Besides the intrinsic development of force by the muscles due to recruitment of motor units and increase of their firing rates, the amount of force acting on the centre of mass also depends on movement conditions, i.e. the contraction dynamics or the transfer of force to the ground. According to the force-velocity relationship (Hill 1938), the force a muscle is able to develop is related to its contraction velocity. Higher forces are related to lower contraction velocities or even zero or negative contraction velocities during isometric or eccentric contractions, respectively. In addition, the force-length relationship (Gordon et al. 1966) is determining the force which a muscle can develop depending on its length. The muscle force is then transferred via the tendons to the bones and subsequently to the ground. This is influenced by the properties of the tendons and the jumping surface (shoes and floor type).

Intrinsic muscle properties like neural activation capacity, force-velocity relationship and force-length relationship can be altered by training (Widrick et al. 2002) within individual boundaries. Simulation studies (Thaller et al. 2010) have shown that individuals have to alter specific aspects of their muscle properties to increase jumping height. This indicates the importance of individualized training. While some athletes would have to increase their maximal force, others might have a deficit in maximum contraction velocity or maximum power capacity. Since the amount of time during a jump movement is limited, the increase of force which is related to the neural activation capacity also affects the jumping height. Besides simulations, regression analyses on experimental data have shown that in general the capacity to develop high mechanical power during the push-off phase is closely related to jumping height (Aragon-Vargas und Gross 1997). The general importance of muscular power is also underlined by the results of the review by (Ziv und Lidor 2010) who pointed out the success of explosive plyometric training to increase jump height in volleyball players.

Different techniques like a counter movement or the use of arm swings have substantial effects on jumping height. A counter movement, i.e. a lowering of the CoM before the upward movement during the push-off phase increases the jumping height by around 7 % (Bobbert und van Ingen Schenau, G J 1988; Wagner et al. 2009). The causes for this increase are an increased myoelectrical activity in the stretch-shortening-cycle (SSC, (BOSCO et al. 1982), the storage and recoil of elastic energy (Kurokawa et al. 2003), and a greater level of active state (Bobbert et al. 1996). Lees et al. (2004) and Hara et al. (2006) have reported an increase of jumping height by 19-23 % due to the use of an arm swing. The reasons for this improvement are an increased centre of mass (due to the already elevated arms at take-off) and a decrease of contraction velocity of the leg muscle which leads to an increase in muscle force due the force-velocity relationship. Another important movement condition is the surface where the jump is performed. (Giatsis et al. 2004) have shown experimentally that jumps on sand are 14 % lower than jumps from a rigid surface. The reason for this decrease is the energy absorbed by the soft surface due to the mechanical work done on the surface, i.e. the sand. Similar, but less substantial effects can be expected by different shoe sole or indoor surface materials. Although stiff materials have advantages during the take-off, they will also absorb less energy during the landing phase which might lead to higher stress in the athlete’s lower limb joints.

Jumping is a specific skill of volleyball players which is underlined by studies that reported greater counter movement jumping heights reached by volleyball players compared to athletes from soccer, handball, basketball, or rowing (Kollias et al. 2004). Furthermore, recent findings

(Sattler et al. 2014) revealed that volleyball players from the first division jump higher than their colleagues from the second division in Slovenia.

b. Spike and serve jumps

In order to smash the volleyball in the court of the opponent, athletes try to reach the greatest possible jumping height during their spike jump. The volleyball spike jump technique includes a three step approach with a two-legged jump, a countermovement, and the use of an arm swing (Wagner et al. 2009). Due to this favorable movement conditions, spike jump (SPJ) heights are greater than heights reached during squat jumps (SJ) or counter movement jumps (CMJ) from a standing position. While SPJ are reported to be approx. 25 % higher than CMJ (Maffiuletti et al. 2002; Sheppard et al. 2008), CMJ are about 7 % higher than SJ (Wagner et al. 2009; Bobbert et al. 1996).

The kinematics of the volleyball SPJ was early analyzed by (Coleman et al. 1993). Lately, (Wagner et al. 2009) have analyzed SPJ technique and identified the most important kinematic parameters related to the volleyball SPJ height. SPJ height correlated significantly with the maximal horizontal velocity of the centre of mass (CoM) and with the minimum height of the CoM during the three step approach in high-level athletes. Thus, within the measured ranges a faster approach and a lower squat during the jump preparation (see Fig. 1) were related with greater jumping heights.

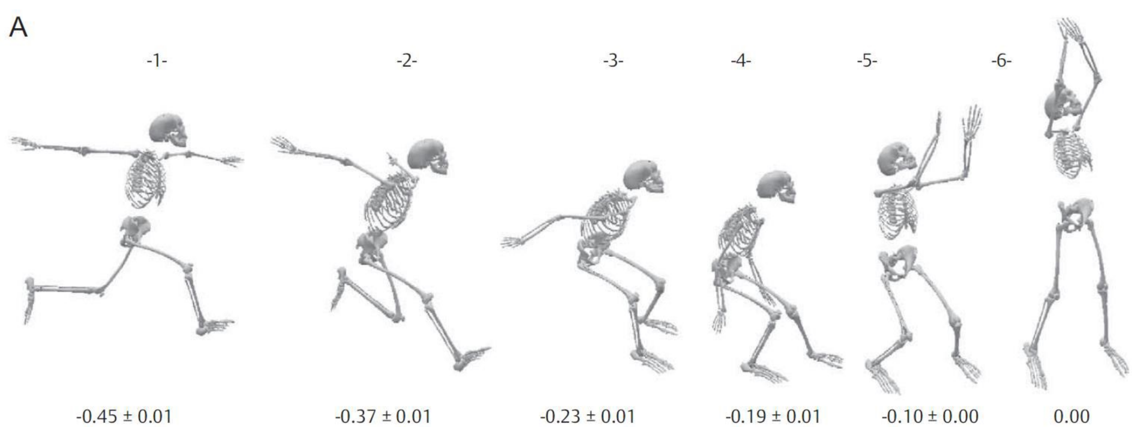

Figure 1: The last two steps of the three step approach of a volleyball spike jump: 1-2 approach phase, 2-4 downward phase, 4-6 upward phase (adapted from Wagner et al. (2009), with permission)

Although the SPJ is a two-legged jump, only the range of motion (RoM) of the right knee flexion extension and the maximal angular velocity of the left shoulder hyperextension were significantly related to jumping height. The reason for this is probably that the SPJ is rather asymmetrical as can be seen in Figure 1. (Wagner et al. 2009) found out that during the upward phase the right foot is closer to the CoM than the left foot and therefore would contribute predominantly to the vertical acceleration of the CoM. Another asymmetry can be observed in the upper body. Figure 1 shows the trunk rotation around the vertical axis in order to increase the acceleration path of the hitting arm.

c. Block jumps

Similar to a soccer goalkeeper acting against an approaching attacker, block players try to decrease the attacking angle of the spiker by overreaching the net with their arms. Mechanically, this produces an angular momentum around the transversal axis. Since the blocking player is in the air during the jump, the laws of physics implicate a preservation of (angular) momentum. Hence, the momentum by the arms has to be counteracted by an opposite (angular) momentum of a different body part. If this compensation movement is not actively executed by the legs (Figure 2), the compensation might occur by a backward movement of the trunk which is not desired because it decreases the overreaching of the arms and might open a gap between the arms and the net. Compensation of the angular momentum of the arms by the lower extremities can also be observed around the anterior-posterior axis (Figure 2). In order to avoid a technical mistake by touching the line or an uncontrolled landing, these angular impulses have to be reversed during the landing.

Figure 2: Upper body movement compensated by lower body movements around the transversal (left picture) and anterior-posterior axis (right picture) during block movements (from www.fivb.ch, with permission).

d. Landing

What goes up must come down - it is inevitable to land following a jump. During the downward phase of a jump the athlete increases his/her downward momentum due to gravity. This momentum must be decreased during the touch down phase by the ground reaction force acting on the body. Depending on the surface (hard/soft) or the muscle activation and hence the stiffness of the legs, the peak ground reaction forces can vary substantially during the landing and the peak forces and loading rate generally exceed those during the take-off movement. Such high forces are related to high stress in the lower limb joints and may cause acute and overuse injuries like anterior cruciate ligament ruptures or patellar tendinopathies, respectively (Bahr und Reeser 2003).

In volleyball, several factors influence the ground reaction force during landing. The landing surface affects the forces that are acting on the athletes. Stiffer surfaces will lead to higher forces. This is in line with the fact that elite beach volleyball players that play on soft sand surface are less vulnerable to patellar tendinopathies compared to indoor players (Lian et al. 2005). Similarily, the stiffness of the shoes will influence the developed forces during landings following a jump (DeBiasio et al. 2013). Besides the environmental factors also the activation pattern and landing techniques will affect forces during landings substantially. (Lobietti et al. 2010) analyzed landing patterns (left or right foot or both feet together) in high-level volleyball and reported e.g. differences between the sexes in block, set, and spike but not for the jump serve. Furthermore, one foot landings with higher risk of injuries were related to court position and setting trajectory. Athletes that spiked faster sets were more likely to land on one foot.

e. Differences between indoor and beach volleyball

Although the playing concept and game idea of indoor and beach volleyball is quite similar, techniques of these athletes vary significantly from a biomechanical point of view due to different movement conditions, i.e. sand compared to indoor surface or the number of players. When comparing the spike technique of these types of sport, (Tilp et al. 2008) found out that beach volleyball players adapt their techniques to the softer sand surface. They slowed down their movements, especially during the eccentric-concentric phase at maximum knee flexion and during the acceleration phase. On sand, players decrease their CoM lower than indoors (see Figure 3) to reach maximum jumping height. Furthermore, beach volleyball players placed their feet more parallel and flat on the ground compared to indoor players. The authors hypothesized that the flatter sole contact on sand increases the contact area where force can be distributed and therefore may decrease the sinking process.

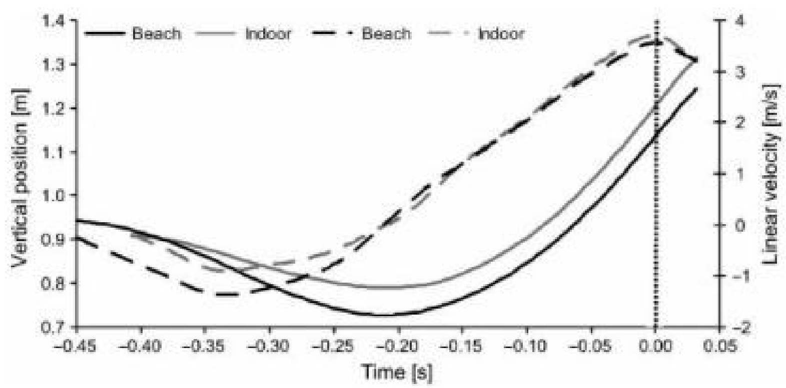

Figure 3: Vertical position (solid lines) and linear velocity (dotted lines) of the centre of mass during a beach volleyball (black) and an indoor volleyball (grey) spike jump (from).

While the sand surface has disadvantages regarding the jumping height, it has advantages regarding the landing. Besides the lower jumping height, which results in a lower downward momentum, also the yielding property of sand decreases forces during the landing compared to hard surfaces. At touch-down the downward momentum must be decreased by the ground reaction force acting on the body. On a softer surface the sum of the ground reaction force is distributed over a greater distance (due to the greater penetration in the sand compared to a hard surface in the gym) and greater time. Thus, the maximum force on a sand surface is smaller compared to a hard surface. Furthermore, the playing concept of beach volleyball with only two players is slower compared to indoor volleyball. Because it is obvious who is playing the next ball within a team, fast sets and surprising tactics are not as effective as in indoor volleyball. This results in more controlled landings on both feet on the sand following most of the techniques especially in men (Tilp und Rindler 2013) which might be one reason for less acute and overuse injuries in beach compared to indoor volleyball. Only following sets beach volleyball players land more often on one foot compared to their indoor colleagues. The reason for this is that beach volleyball players have less time to reach the setting position because at the time of the serve it is not yet clear who of the two players will set the ball.

2. Spiking

Similar to other sports like team handball, tennis or baseball, an overarm technique is used during the spike to accelerate the volleyball. While players in handball or baseball throw the ball and tennis players hit the ball with a racket, indoor or beach volleyball players hit the ball with their hand to score a point. At the instant of the spike a momentum (=mass·velocity) is transferred from the hand to the ball from a mechanical point of view. Besides the two parameters mass and velocity, the elastic properties of the ball and the hand affect the result, i.e. the ball velocity. The mass and elastic property of the ball is regulated by the FIVB. The elastic property of the hand and the mass acting on the ball can be regulated by muscle activation of the athlete. Briefly, the stiffer the hand and the more mass is included (i.e. the interacting of hand, arm, shoulder and trunk) the greater the momentum which is transferred to the ball. This is however an optimization process since a fusion of the acting body parts to one mass by muscle activation would also decrease the overall movement velocity. The body solves this by a coordinated proximal-to-distal sequencing of the maximum velocities of the interacting body parts (Wagner et al. 2014). (Coleman et al. 1993) determined that maximal humerus velocity was associated with high post-impact ball speed. Furthermore, an increase in ball speed can be achieved by an increase in pelvis, trunk and shoulder rotation in the preparation phase of the spike which increases the range of motion. (Li Fang et al. 2008, 2008) reported that a high range of motion is a key factor of the spiking technique and differentiates beginners from high-level athletes. During the preparation phase and at the instant of the spike the volleyball athlete is in the air and therefore, similar to the block movement, the laws of physics implicate a preservation of (angular) momentum. Hence the momentum by the upper body has to be counteracted by an opposite (angular) momentum of the lower body, i.e. a hip extension and knee flexion during the preparation phase and a hip flexion and knee extension at the instant of the ball hit (Figure 4).

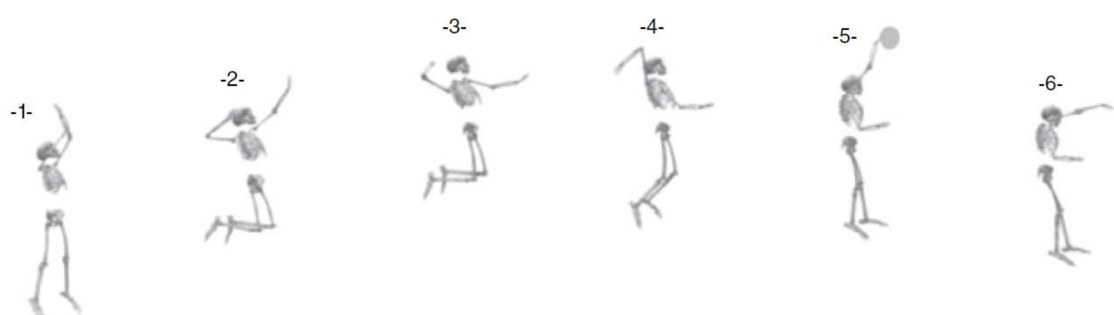

Figure 4: Aerial phase of the spike jump including the smash: 1–3 cocking phase, 3–5 acceleration phase, 6 follow-through phase. Source: adapted from Wagner et al. (2014). Reproduced with permission of John Wiley & Sons.

3. Physics of the ball trajectory

Depending on the volleyball technique, ball trajectories are slightly different. During a set the trajectory will be approximately parabolic because the ball has low velocity and no rotation. Hence, besides the gravity this parabolic trajectory is determined by the initial position, take-off angle, and -velocity at the instant of the set (Figure 5).

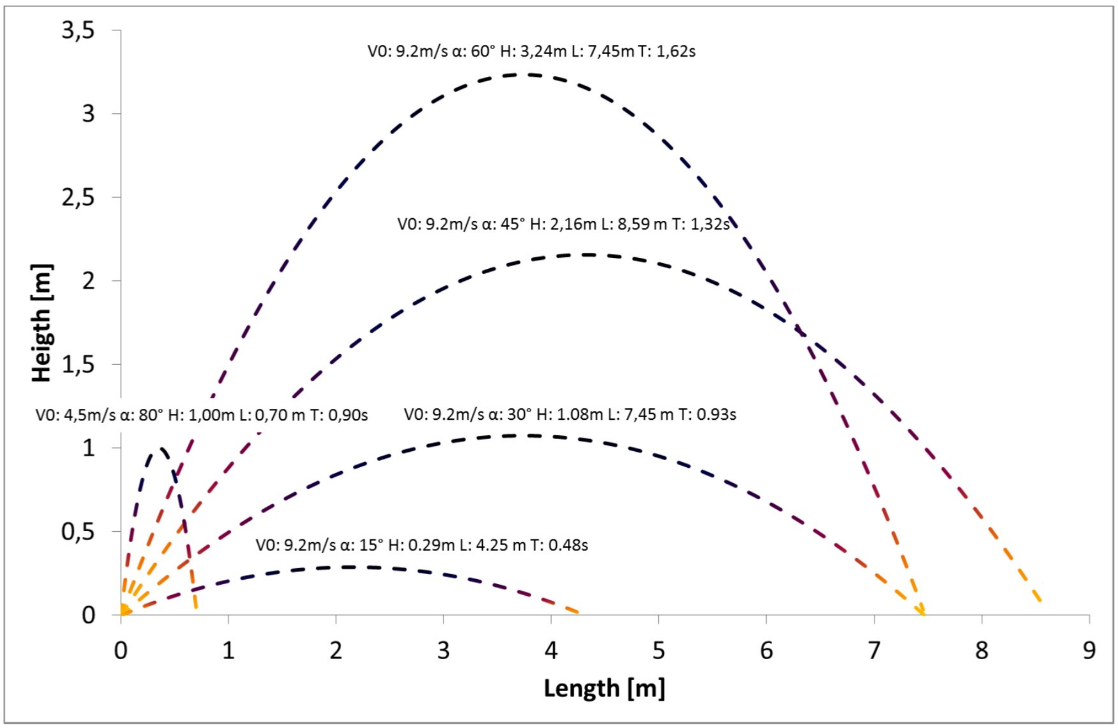

Figure 5: Different parabolic setting trajectories related to take off velocity (V0), take off angle (α). Please note the maximal height (H), length (L) and especially the time (T) of the sets.

Contrary, when the ball flies with a higher velocity, air resistance affects the trajectory significantly. Air resistance, described in Equ. (iii), is related to the drag coefficient (C_D), the air density (ρ, 1.2 kg/m³), the projected area of the volleyball (A), and the velocity (V). An important factor influencing air resistance (through the drag coefficient C_D) is the boundary layer, defined as a thin layer of air near the surface, which the ball carries with. During the flight this boundary layer will peel away from the surface at the back of the ball and has two distinct states: “laminar” and “turbulent”. While in the laminar state, tiers are laid one on top of each other, in the turbulent state the air is moving chaotically. A turbulent state is related with a smaller wake behind the ball and therefore a smaller drag coefficient and thus to lower air resistance. The transition from laminar to turbulent state occurs when a critical Reynolds number, which depends on velocity and ball surface (Metha und Pallis 2001), is achieved where C_D drops abruptly. Interestingly, critical Reynolds numbers of *Re*=220.000-270.000 for volleyballs ((Asai et al. 2010) occur at typical volleyball spike or service velocities and therefore lead to deviations of the trajectory. During a float swerve this process leads to irregular non-symmetrical lateral forces acting on a ball and leading to unpredictable trajectories (Qing-ding et al. 1988). Due to structure differences in the surface of volleyballs of different producers in the past (smooth, honeycomb, dimples), volleyballs have also changed their floating properties and therefore trajectories (Asai et al. 2010).

iii) $F_D = \frac{1}{2} \cdot C_D \cdot \rho \cdot A \cdot v^2$ iv) $\mathrm{F}_L = \frac{1}{2} \cdot C_L \cdot \rho \cdot A \cdot v^2$

In a rotating ball, the so-called Magnus-effect alters the ball trajectory by introducing a lift force (F_L , see equation (iv) including a lift coefficient C_L) in the direction of the ball rotation. Initially, the German physicist Heinrich Gustav Magnus has explained this by different streaming velocities and resulting in different pressure (Bernoulli Effect) on the different sides of the ball. Later the American physicist Lyman J. Briggs explained this effect by a turbulent wake behind the spinning ball. (Metha und Pallis 2001) explained that the rotation of a ball leads to an asymmetric separation of the boundary layer and therefore to a wake deflected in the opposite direction of the rotation. Following Newton's 3rd Law of Motion the deflected wake implies a (Magnus) force on the ball and thus a curved trajectory. Thus, service or spikes with a topspin rotation are deflected downwards (Figure 6). Consequently, a ball that was spiked over the opponent's block with topspin rotation might still hit the ground within the court while a ball without spin or even backward spin would be out. Similarly, a topspin serve will come down closer to the net or can be played with higher velocity due to its downward deflection.

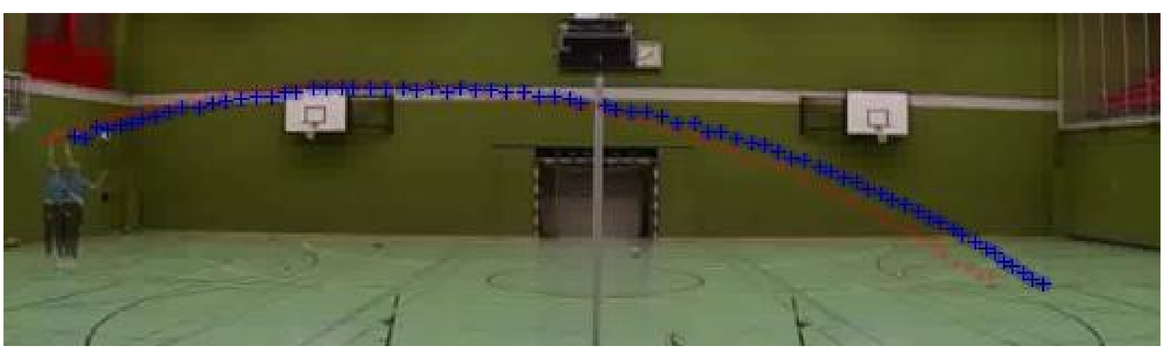

Figure 6: Comparison of the ball trajectory of a topspin serve (light crosses) and loat serve (dark crosses) at similar serve speed of ~14 m/s. Note that the path of the topspin serve is delected downward.

Based on the knowledge of the influence of ball rotation on the trajectory and further experimental data, (Kao et al. 1993)) has made simulations to find out the optimal spike position on the court against a block with two blockers. They defined the optimal spike position as the coordinates from where an attacker has the greatest possible attacking angle against a central double block of 1.2 m width. They used a ball velocity of 20 m/s and an angular velocity of 7 revolutions/s. Including this information they calculated an optimal spike position with an attacking angle of 30° at 1.6 to 2.5 m behind the middle line and 0 – 1.5 m from the side line from position II or IV on the volleyball field. This underlines the excellent spiking conditions for back row spikers.

4. Summary and conclusion

Biomechanics in volleyball is important for maximal performance and regarding injury prevention. Maximal jumping heights are achieved by maximizing take-off velocity. This is supported by a countermovement and the use of an arm swing and will be decreased by a yielding surface like sand.

During the aerial phase of serve-, spike- or block movements the (angular) momentum is preserved. Therefore, angular moments produced by the arms are compensated by other body parts. This coordinate processes should be trained in order to use adequate techniques. During the overarm spike technique the momentum (mass·velocity) of the hand is transferred to the ball. Coordinated muscle activity increases the momentum and the elastic properties of the hand.

Acting forces during the landing phase are influenced by the landing surface and technique. A yielding surface and landing on two feet will reduce force peaks and therefore injury risk.

The volleyball trajectory is greatly affected by velocity and rotation. While setting trajectories are approximately parabolic, following spikes and serves at critical velocities the boundary layer around the ball peels away in a turbulent state behind the ball which makes the trajectory less predictable. A rotation on the ball leads to an asymmetric separation of the boundary layer and therefore to a deflection in the opposite direction of the rotation.

References

Aragon-Vargas, Luis F.; Gross, Melissa (1997): Kinesiological Factors in vertical jump performance: Differences among individuals. In: *Journal of applied biomechanics* 13 (1), S. 24–44.

Asai, Takeshi; Ito, Shinichiro; Seo, Kazuya; Hitotsubashi, Akihiro (2010): Aerodynamics of a new volleyball. In: *Procedia Engineering* 2 (2), S. 2493–2498. DOI: 10.1016/j.proeng.2010.04.021.

Bahr, Roald; Reeser, Jonathan C. (2003): Injuries among world-class professional beach volleyball players. The Fédération Internationale de Volleyball beach volleyball injury study. In: *The American journal of sports medicine* 31 (1), S. 119–125.

Bobbert, M. F.; Gerritsen, K. G.; Litjens, M. C.; Van Soest, A J (1996): Why is countermovement jump height greater than squat jump height? In: *Medicine and science in sports and exercise* 28 (11), S. 1402–1412.

Bobbert, M. F.; van Ingen Schenau, G J (1988): Coordination in vertical jumping. In: *Journal of biomechanics* 21 (3), S. 249–262.

BOSCO, C.; TIHANYI, J.; KOMI, P. V.; FEKETE, G.; APOR, P. (1982): Store and recoil of elastic energy in slow and fast types of human skeletal muscles. In: *Acta Physiologica Scandinavica* 116 (4), S. 343–349. DOI: 10.1111/j.1748-1716.1982.tb07152.x.

Coleman, S. G.; Benham, A. S.; Northcott, S. R. (1993): A three-dimensional cinematographical analysis of the volleyball spike. In: *Journal of sports sciences* 11 (4), S. 295–302. DOI: 10.1080/02640419308729999.

DeBiasio, Justin C.; Russell, Mary E.; Butler, Robert J.; Nunley, James A.; Queen, Robin M. (2013): Changes in Plantar Loading Based on Shoe Type and Sex During a Jump-Landing Task. In: *Journal of Athletic Training* 48 (5), S. 601–609. DOI: 10.4085/1062-6050-48.3.08.

Giatsis, George; Kollias, Iraklis; Panoutsakopoulos, Vassilios; Papaiakovou, George (2004): Biomechanical differences in elite beach-volleyball players in vertical squat jump on rigid and sand surface. In: *Sports biomechanics / International Society of Biomechanics in Sports* 3 (1), S. 145–158. DOI: 10.1080/14763140408522835.

Gordon, A. M.; Huxley, A. F.; Julian, F. J. (1966): Tension development in highly stretched vertebrate muscle fibres. In: *The Journal of physiology* 184 (1), S. 143–169.

Hara, Mikiko; Shibayama, Akira; Takeshita, Daisuke; Fukashiro, Senshi (2006): The effect of arm swing on lower extremities in vertical jumping. In: *Journal of biomechanics* 39 (13), S. 2503–2511. DOI: 10.1016/j.jbiomech.2005.07.030.

Hill, A. V. (1938): The Heat of Shortening and the Dynamic Constants of Muscle. In: *Proceedings of the Royal Society B: Biological Sciences* 126 (843), S. 136–195. DOI: 10.1098/rspb.1938.0050.

Kao, S.; Sellens, R.; Stevenson, J. (1993): The trajectory of the spiked volleyball. In: *Journal of biomechanics* 26 (3), S. 307. DOI: 10.1016/0021-9290(93)90433-F.

Kollias, Iraklis; Panoutsakopoulos, Vassilios; Papaiakovou, Georgios (2004): Comparing jumping ability among athletes of various sports: vertical drop jumping from 60 centimeters. In: *Journal of strength and conditioning research / National Strength & Conditioning Association* 18 (3), S. 546–550. DOI: 10.1519/1533-4287(2004)18<546:CJAAAO>2.0.CO;2.

Kurokawa, Sadao; Fukunaga, Tetsuo; Nagano, Akinori; Fukashiro, Senshi (2003): Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. In: *Journal of applied physiology (Bethesda, Md. : 1985)* 95 (6), S. 2306–2314. DOI: 10.1152/japplphysiol.00219.2003.

Lees, Adrian; Vanrenterghem, Jos; Clercq, Dirk de (2004): Understanding how an arm swing enhances performance in the vertical jump. In: *Journal of biomechanics* 37 (12), S. 1929–1940. DOI: 10.1016/j.jbiomech.2004.02.021.

Li Fang, L.; Gin-Chang, L.; Chiao-Wen, S.; Chen-fu, H. (2008): The application of range of motion (ROM) an coordination on volleyball spike. In: Young-Hoo Kwon, Jaeho Shim, Jae Kun Shim, In-Sik Shin (Hg.): ISBS Conference Proceedings 2008. ISBS. Seoul, Korea, 14.-18.7. Seoul, Korea.

Lian, Oystein B.; Engebretsen, Lars; Bahr, Roald (2005): Prevalence of jumper's knee among elite athletes from different sports: a cross-sectional study. In: *The American journal of sports medicine* 33 (4), S. 561–567. DOI: 10.1177/0363546504270454.

Lobietti, Roberto; Coleman, Simon; Pizzichillo, Eduardo; Merni, Franco (2010): Landing techniques in volleyball. In: *Journal of sports sciences* 28 (13), S. 1469–1476. DOI: 10.1080/02640414.2010.514278.

Maffiuletti, Nicola A.; Dugnani, Sergio; Folz, Matteo; Di Pierno, Ermano; Mauro, Franco (2002): Effect of combined electrostimulation and plyometric training on vertical jump height. In: *Medicine and science in sports and exercise* 34 (10), S. 1638–1644. DOI: 10.1249/01.MSS.0000031481.28915.56.

Metha, R. D.; Pallis, J. M. (2001): Sports Ball Aerodynamics: Effects of Velocity, Spin and Surface Roughness. In: F. H. Froes und S. J. Haake (Hg.): Materials and Science in Sports. Materials and Science in Sports. Coronado, Califronia, US, 22.-24.4., S. 185–197.

Qing-ding, Wei; Rong-sheng, Lin; Zhi-jie, Liu (1988): Vortex-induced dynamic loads on a non-spinning volleyball. In: *Fluid Dyn. Res.* 3 (1-4), S. 231–237. DOI: 10.1016/0169-5983(88)90071-8.

Sattler, Tine; Hadžić, Vedran; Dervišević, Edvin; Markovic, Goran (2014): Vertical jump performance of professional male and female volleyball players: effects of playing position and competition level. In: *Journal of strength and conditioning research / National Strength & Conditioning Association. DOI:* 10.1519/JSC.0000000000000781.

Sheppard, Jeremy M.; Cronin, John B.; Gabbett, Tim J.; McGuigan, Michael R.; Etxebarria, Naroa; Newton, Robert U. (2008): Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. In: *Journal of strength and conditioning research / National Strength & Conditioning Association* 22 (3), S. 758–765. DOI: 10.1519/JSC.0b013e31816a8440.

Thaller, Sigrid; Tilp, Markus; Sust, Martin (2010): The effect of individual neuromuscular properties on performance in sports. In: *Mathematical and Computer Modelling of Dynamical Systems* 16 (5), S. 417–429. DOI: 10.1080/13873954.2010.507082.

Tilp, Markus; Rindler, Michael (2013): Landing techniques in beach volleyball. In: *Journal of sports science & medicine* 12 (3), S. 447–453.

Tilp, Markus; Wagner, Herbert; Müller, Erich (2008): Differences in 3D kinematics between volleyball and beach volleyball spike movements. In: *Sports biomechanics / International Society of Biomechanics in Sports* 7 (3), S. 386–397. DOI: 10.1080/14763140802233231.

Wagner, H.; Pfusterschmied, J.; Tilp, M.; Landlinger, J.; von Duvillard, S. P.; Müller, E. (2014): Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. In: *Scand J Med Sci Sports* 24 (2), S. 345–354. DOI: 10.1111/j.1600-0838.2012.01503.x.

Wagner, H.; Tilp, M.; von Duvillard, S P; Mueller, E. (2009): Kinematic analysis of volleyball spike jump. In: *International journal of sports medicine* 30 (10), S. 760–765. DOI: 10.1055/s-0029-1224177.

Widrick, Jeffrey J.; Stelzer, Julian E.; Shoepe, Todd C.; Garner, Dena P. (2002): Functional properties of human muscle fibers after short-term resistance exercise training. In: *American journal of physiology. Regulatory, integrative and comparative physiology* 283 (2), S. R408-16. DOI: 10.1152/ajpregu.00120.2002.

Ziv, G.; Lidor, R. (2010): Vertical jump in female and male volleyball players: a review of observational and experimental studies. In: *Scandinavian Journal of Medicine & Science in Sports* 20 (4), S. 556–567. DOI: 10.1111/j.1600-0838.2009.01083.x.