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GYMNASTICS

Gymnast/Apparatus Interaction for Coaches

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“The bar is a trampoline...if you’re tight.” Coach David Seiler

The interaction between gymnast and apparatus is rarely considered in analyzing gymnastics performance (Sands, et al., 2014). And yet, we coaches know that how the gymnast uses a bar or a spring floor is important. The two participants in this interaction are the **gymnast** interacting with the **apparatus**. The characteristics of each, gymnast and apparatus, strongly influence how this interaction works. And we will see that this interaction is essential to understand skill technique.

The Gymnastics Apparatus

Gymnastics equipment bends, flexes, recoils, and then returns to its original shape. The springboard and floor are mounted on steel springs. The high bar is actually made of spring steel, but also uneven bars and parallel bar rails bend, recoil, and vibrate. A ring tower is constructed with some “give” as well as having springs in the cable mounts of each ring. Even the balance beam is mounted on rubber blocks so that the aluminium beam will give a little during landings and push back during takeoffs. The exception is the pommel horse, which is padded, but has no elasticity to speak of, even in the pommels. The other extreme are trampolines, mini-tramps, double-minis, and tumbling tramps that are more like a diving springboard.The various apparatus are elastic.

Gymnastics apparatus is mechanical equipment that is elastic and will oscillate. In the case of gymnastics equipment, the word “vibration” describes mechanical oscillation. A bouncing metal spring is a common example of mechanical oscillation or vibration. Oscillation or vibration is repeating motion of a body back and forth around a starting, resting position. The gymnast can push the apparatus down, changing its shape, and the apparatus will store that energy in its shape change. Then the apparatus will first return to its original shape and then past that original shape, changing that stored energy into kinetic energy, the energy of movement.

Simple vibrations describe how an elastic object that is pushed out of place stores a correcting force that tries to restore it. But this force not only restores the object to its original shape but past it. Overshooting the starting point, it wobbles back and forth until it settles back into its original position. In simple vibration, the correcting force always opposes the object’s motion and scales with the distance it is moved. So as the object is moved further away, it feels a stronger force pushing it back. Released, it is flung out the other way and, like a child on a swing, feels a push backward that eventually stops it and sends it back again. So it oscillates back and forth.

The path traveled by a point on a piece of vibrating gymnastics equipment can be described by a sine wave (Fig. 1). This mental trick is very helpful for gymnastics scientists because the physics and mathematics of sine waves have been thoroughly investigated for hundreds of years and are very well understood. Imagine that you are down on your stomach, looking at a spring floor from the side, at floor level. We record the motion of the floor with a high speed camera because it moves so fast and then graph the positions of the floor panel over time. If a gymnast “punches” the floor at the left of Fig. 1. the floor will move like the wave in Fig. 1. As we look from left to right, the gymnast drives the motion of the spring floor: from its resting position at the left, the floor will be pushed down, before returning to its original position, and then recoil up above it, before finally returning to rest after the gymnast takes off at time 1. Ideally, for the highest salto the gymnast will leave the floor at the top of the red “Amplitude” line.

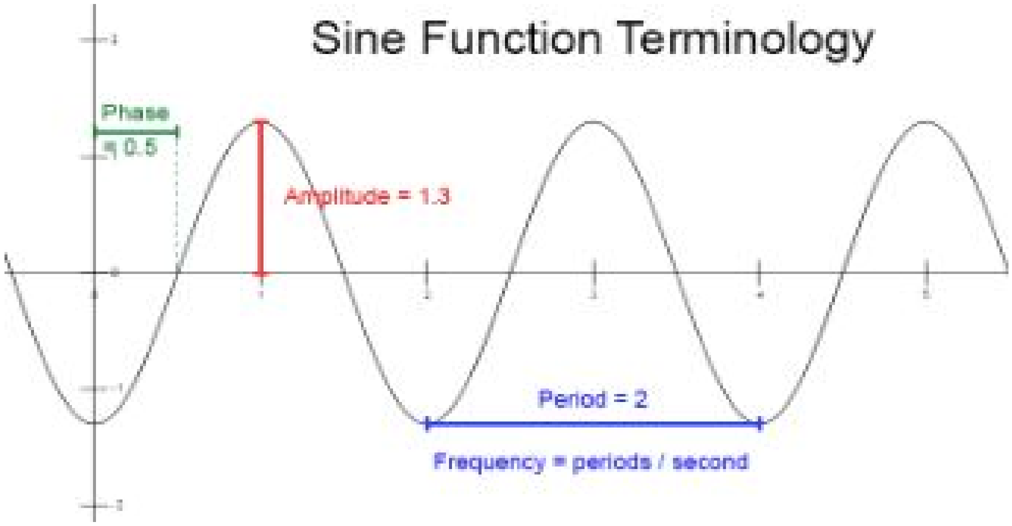


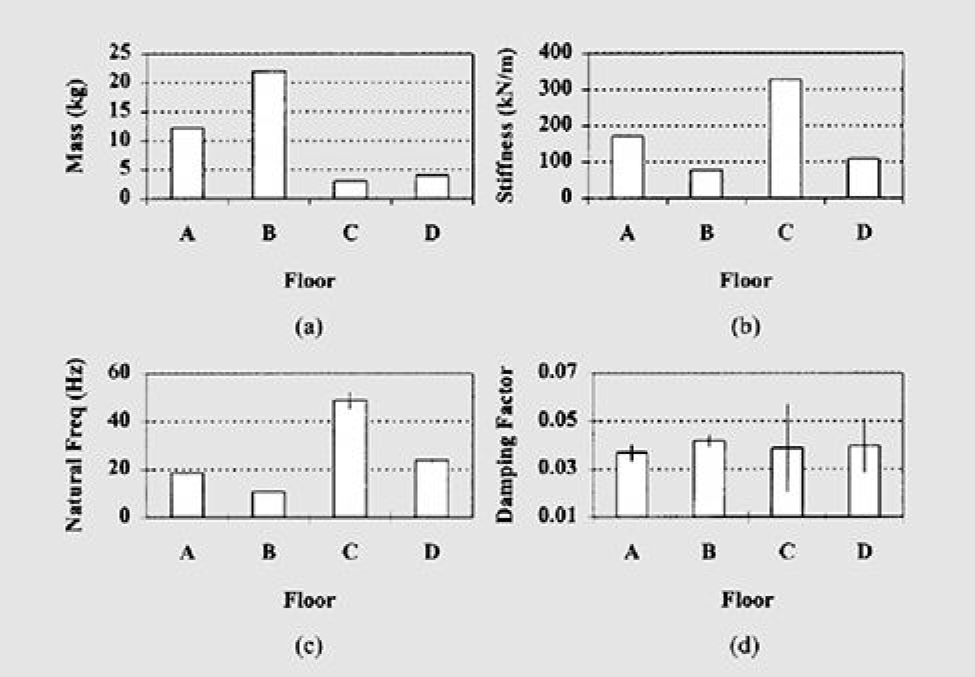
Fig. 1. The sine function wave. Time moves from left to right. The vertical bar shows displacement from the resting position which is the horizontal line.

The movement of oscillating bodies like a spring floor or high bar are characterized by just two numbers, the **frequency** and **amplitude**. The number of repetitions per unit of time is the frequency of vibration. Vibrations are periodic processes; they repeat every certain amount of time. How long a repeating event takes to complete one repetition is its period, so the period is the mathematical reciprocal of the frequency. For example, if a high bar vibrates 6 times in one second, a frequency of 6/second, the time between each vibration - its period - is one/sixth of a second, or about 17/100 second. The amplitude of a vibration is the distance it travels in one direction from its resting position. The **phase** is the direction the wave is moving at any certain time, in our example up- or downwards. Phase is usually given as the angle of an arrow pointing in the direction the wave is moving. Both the frequency and the amplitude of a vibrating piece of gymnastics equipment are important for gymnastics technique and performance.

Of course, the example wave pictured in Fig. 1. is completely theoretical because in practice, a vibrating gymnastics apparatus rapidly quiets down. This is called **damping**. If Fig. 1. was showing a damped vibration, as the wave moved from left to right in time, the amplitudes of each wave would get smaller and smaller. For example, a spring floor is heavily damped by the 2 inch thick layer of foam and carpet lying on top of the floor panels. The foam and carpet are not glued to the floor panel, so when the foam and carpet are pushed up by the recoil of the spring floor underneath, they don't necessarily go back down as fast as the spring floor panel. Now foam and carpet are out of phase with the floor movements. In other words, the floor panel may be moving up again, driven by a second recoil of the springs, while the foam and carpet are falling back down, in the opposite direction. Foam and carpet will eventually slap the floor panel back down as the floor panel is moving up again, opposing and thereby quickly damping out the floor movements. We have all seen a gymnast "ping" off a high bar, leaving the bar vibrating rapidly. A high bar is much less damped, but the bar's vibrations also eventually die out, mainly due to friction between the two ends of the bar and their mounts.

Vibrating bodies have a **natural frequency**, the frequency at which the body oscillates when there are no driving or damping forces. A vibrating body's natural frequency quantifies its free vibrations. Each piece of gymnastics equipment has its own, characteristic, natural frequency of vibration. Spring floors that feel "hard" to the gymnast have a higher natural frequency than a floor that feels "bouncy". In some cases, for example the high bar, this natural frequency can be adjusted somewhat with the cable tension. However, an external force can also be driving the motion of a vibrating body. Examples of an external force driving the vibration of a gymnastics apparatus would be the take-off to a back salto or bending the high bar with a "Chinese tap". The forced vibrations of a body then happen at the frequency of the driving force. If the frequency of the force driving an oscillating body is close to the body's natural frequency, the resulting motion is greatest. When the frequency of the driving force is the same as the natural frequency, and in phase with the vibration, the amplitude of the vibration increases spectacularly. This result is known as **resonance**. This frequency is called the resonant frequency. In a mass-spring system, like a spring board, with mass **m** and spring stiffness **k**, the natural frequency ω and therefore the resonant frequency is $\omega = \sqrt{k/m}$ (den Hartog, 1985). The important elements are the mass of the vibrating apparatus and its stiffness. Mass is a key characteristic of the weight of an apparatus or and its resistance to a change in its motion. Stiffness is the force that resists a change in shape of the apparatus. The formula tells us that as the stiffness increases, the natural frequency gets faster, and as the mass increases, the natural frequency gets slower. Spring floors, for example, have mass and stiffness, and a natural frequency. See Fig. 2. from Paine, 1998. Floor A in Fig. 2 is a spring floor approved for competition. Floors B, C, and D are experimental floors. We see that the mass of Floor B is increased with added weight, its stiffness is less compared with Floor A, and its natural frequency is slower.

Fig. 2. Characteristics of four different spring floors. From Paine, 1998



Although a child's swing set is not a mass-spring system like most gymnastics apparatus, pushing a child in a swing is a popular example of a forced oscillation and resonance. Moreover, a swinging motion is closely related mathematically to the up-and-down vibration of a mass and spring system. If the parent pushes the child in the swing as the swing is moving away, the amplitude of the swing can increase. The parent's push is a driving force in phase with the oscillation of the child. If the parent pushes against the child as the child is moving back towards the parent, the amplitude of the swing decreases or even stops. This is a driving force out of phase with the swing, damping the amplitude of the swing. If the parent pushes the child exactly in frequency and phase with the swing, as the swing is moving away, the amplitude of the swing can increase enormously. This is the resonance phenomenon. Engineers usually want to eliminate resonance effects because as the amplitude of the vibrations increase, they can shake a bridge or engine apart. However, gymnasts are interested in getting resonance effects from gymnastics apparatus to fly higher, just like the child in the swing set.

Why are trampolines, mini-tramps, double-minis, and tumbling tramps more like a diving springboard than a gymnastics apparatus? The slow period and large amplitude of the bounce. We can see with the naked eye how a skilled diver drives a diving springboard down and then stiffens to then ride it up again and off into an airborne, acrobatic dive, because it all happens so slowly. A gymnast on a trampoline is a little faster, but the action is the same. The same process is happening when a skilled gymnast “punches” a spring floor, only even faster. Like the diver, the gymnast does not squat down and then jump, but rides the recoil of the equipment. This puts a premium on the gymnasts ability to stay tight, first resisting the impact with the apparatus, the high reaction forces from the gymnastics apparatus resulting from the high speeds, and then resisting the recoil of the equipment. When the gymnast is tight, the recoil of the apparatus then moves the entire gymnast, for example into a salto. When a trampolinist “kills” the bounce of a trampoline by allowing the trampoline to bend their legs, this is an example of pushing out of phase, reducing the amplitude of the trampoline bed and gymnast movement. At much higher frequency, and much smaller amplitude, of both floor and body movements, this is also how a gymnast “sticks” landing on a spring floor.

The Gymnast

Take-offs to saltos, bar dismounts and releases, and blocks off the vault table are example movements in which, in the shortest possible time, the path of the gymnast (center of mass) is changed (Brüggemann, 1989). A gymnast impacts a springboard with the feet, a spring floor with the feet or hands, and a vault table with the hands. Above the bar, gymnasts can push down on the uneven or high bar. Gymnasts can also load the bar by both pulling and using gravity, for example performing a Chinese tap. How the elasticity of the men’s high bar is exploited is of great importance for the execution of airborne skills (Naundorf, et al., 2019).

The top speed sprinting is closely related to vault difficulty score in elite gymnastics. The reason for this relationship between sprinting speed and D-score is that during take-off from the springboard or vaulting table, the horizontal kinetic energy increased by sprinting faster and faster is converted into the angular and vertical kinetic energy that makes the second flight phase (Schärer, et al., 2019). Taking off from a springboard, vaulting table, or spring-floor, horizontal kinetic energy created by sprinting is converted during the gymnast/apparatus interaction into flip and height. When a gymnast hits the spring board or punches the spring floor, they create a vertical impulse that accelerates the body upwards. A vertical impulse is the force acting upwards multiplied by how long it acts. Consequently, a high sprinting speed is a way of creating a big vertical impulse; the force created on the springboard and vault table is what is important for the take-off velocity. Simultaneously, the angular impulse of the entire body is changed by the effect of an eccentric force exchange. The goal of take-offs, blocks, and releases is not maximizing, but optimizing between the translational and rotational velocities, by the end of the time in contact with the apparatus, so that the gymnast can <u>both</u> fly high and flip fast. Consequently, our attention is directed at the force and momentum impulses that cause these changes in velocities (Brüggemann, 1989).

The vertical impulse during take-off or release causes the height of the salto. Vertical impulse during back salto take-off is similar to that of elite track-and-field long jumpers, even though horizontal velocity is much slower in gymnastics. The difference between tumbling take-off and long-jump is made up by the high speed of rotation of the body at the end of a snap-down. The height of a back salto is strongly influenced by how fast the gymnast is turning over during the snap-down. This is a very important fact because this means that the gymnast’s angular momentum immediately prior to take-off is decisive for the height of the salto. The blocking action of the round-off or back handspring landing, the counter angular impulse, then produces brief, but very great forces. The force of the blocking action (counter angular impulse) in the horizontal direction can be 7 times body weight. Ten thousandths of a second after touch-down, there can be peak forces up to 14 times body weight. During the part of the vertical impulse that produces the acceleration of the gymnast upwards, the force can be 10 to 13 times body weight. (Knoll & Zocher, 1979; Brüggemann, 1983).

These exceptional forces require exceptional strength to resist them if the impact is not going to change the shape of the gymnast, causing him or her to more or less collapse. Gymnasts also have mass and stiffness. If the apparatus recoil changes the shape of the gymnast’s body, then kinetic energy is dissipated in heat and movement instead of height and rotation. Moreover, challenges to the gymnast’s ability to stabilize their body, to “stay tight”, are increasing, and have been for many years. Back in 1979 (!), gymnastics scientists K. Knoll and H.-D. Zocher observed that a continuous increase in acrobatic difficulty is a characteristic of the structure of gymnastics performance in competition. Airborne skills in particular have developed immensely over the past decades. Complex airborne skills like dismounts, tumbling, or release moves on bars are performed with more and more flips and twists, as well as greater height. So demands on the coordination abilities have increased. However, this development is based on ever greater vertical and angular impulses that, in turn, make greater challenges to the strength of female and male gymnasts. Yet another aspect is preparing the athletes for the higher reaction forces from the gymnastics apparatus resulting from the higher speeds. For example, as saltos, vaults, and dismounts get higher, the gymnast then has to fall farther, resulting in correspondingly greater impact forces when they land again (Knoll & Zocher, 1979; Sands, et al., 2013).

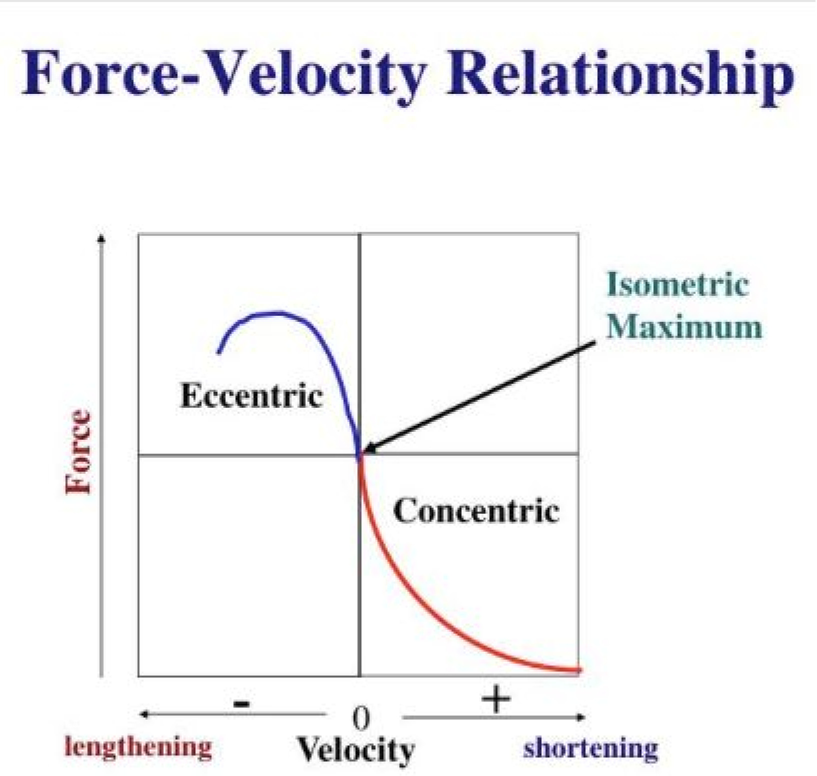


Fig. 3. The relationship between force and velocity of shortening in muscle.

To appreciate what a gymnast must do to “stay tight”, we must understand how muscles produce force, in particular the relationship between force and velocity of shortening of human muscle. This force-velocity relationship describes how the force produced changes when the length of the muscle changes. In the graph below (Fig. 3.), the right side of the central, vertical line is the muscle changing length, shortening (**concentric** contraction). The blue line to the left of the central, vertical line is the muscle trying to shorten, but being lengthened by a superior outside force (**eccentric** contraction), until it tears. When the muscle contracts, but there is no change in length, we have an **isometric**, static, or constant length contraction. The velocity of shortening is zero during an isometric contraction because there is force or tension, but not shortening. When the muscle contraction is producing as much force as it possibly can, but cannot change length because it is resisted by an equal external force, we have the isometric maximum. The curved red line shows us that as soon as a muscle can shorten, the force it can produce falls off dramatically. When a muscle is shortening very rapidly, a muscle produces almost no force. The speed of shortening of the myofilaments that make up muscle is a factor affecting tension development, and therefore force. The rate at which myofilaments slide, form, and re-form cross bridges determines the speed of shortening. The speed of shortening also depends on fiber type and muscle fiber length. Fast-twitch muscle fibers can shorten faster than slow-twitch, and with more force. A longer muscle fiber has more myofilaments attached end-to-end so that when each myofilament slides, the end change in the muscle fiber length is greater than in a shorter fiber, and therefore faster. An isolated muscle can only pull, developing tension, exerting force on whatever the muscle is pulling on. However, acting in the system of levers that is the skeleton, the pull of a muscle can be made into a push.

This force-velocity relationship was worked out by A. V. Hill (1938) in isolated frog muscle. The renowned exercise-physiologist D. Schmidtbleicher (1980) found this relationship in athletic movement. In his doctoral dissertation, Schmidtbleicher researched the relationship between maximum strength and movement quickness, without contaminating the data with movement coordination issues between the training and test skills. With a specially constructed apparatus, the training and test exercises were exactly the same: the bench press. Among many interesting results, Schmidtbleicher showed that the exponential force-velocity relationship that physiologists had been studying in a laboratory, in isolated animal muscles, was also a characteristic of a living, high-performance athlete, performing a common exercise. The force-velocity relationship is relevant to gymnastics and the concerns of coaches, in particular two important points:

- The most force that a muscle can produce is when there is no shortening,
- As soon as there is shortening, force produced drops rapidly (exponentially).

If we remember the enormous forces that are exchanged between gymnast and apparatus, the gymnast clearly must operate on the left side of the force-velocity relationship in Fig. 3., in other words with no shortening, only constant length, or forced lengthening. Consequently, there are two issues of importance for the gymnast in how they interact with the equipment:

- Staying tight, limiting movement, to put as much kinetic energy into the piece of equipment as possible, instead of the apparatus changing the shape of the gymnast, and
- Timing the push or pull that follows the initial contact in order to drive the recoil of the equipment to its highest position: when and how fast force is applied to the equipment, in phase and as close as possible to the apparatus' natural frequency or multiples of that frequency (Arampatzis & Brüggemann,

> 2001). For example, the last back giant swing preparing a layout Tkatchev needs a characteristic three deflections of the high bar, correctly performed in space and time, to transfer energy between gymnast and high bar and make the skill (Fig. 4).

The vibration values of today's gymnastics spring-floor requires that gymnasts control their lower body muscle and tendon stiffness, particularly those muscles and tendons acting on the ankle and knee joints (Arampatzis & Bruggemann, 1999). The stiffness of the passive body elements, for example tendons or bones, contributes to the "tightness" of the gymnast, their ability to hold a shape against the impact and recoil forces. However, gymnasts <u>also</u> control the stiffness of their body with a special kind of coordination called "co-contraction". Co-contraction means that muscles that cause movement in a joint in <u>opposite</u> <u>directions</u> are active at the <u>same</u> <u>time</u>. Co-contraction is used to stiffen the body. An example of co-contraction would be if the rectus femoris of the quadriceps, a knee extender, tensed at the same time as the hamstrings, a knee flexor, each exerting opposing forces at the knee. The result would be a stiffening of the knee. Maximum activation of the upper arm muscles, triceps brachii and the biceps brachii, in a co-contraction would "lock out" the elbow joint. Co-contraction or co-activation is isometric when used to stiffen the joints and limbs, or the body as a whole. For example, Naundorf and co-workers (2008) reported that there had been a big increase in vault sprint speed over the decade between World Championships in 1997 and 2007, by both men and women, even though these were already some of the best vaulters in the world. They also found that vaulters were bending and extending their knees less on the springboard in 2007 than in 1997, hitting the board with a much more isometric muscle action. This development is consistent with hitting the springboard at a higher speed, with correspondingly greater exchange of forces, requiring stronger, stiffer legs.

Forces acting at a joint are basically a load or driving force. Therefore, there should be a close relationship between the amount of force measured for example under a spring floor and the effects of forces acting on a joint. But this assumption depends on the amount of co-contraction effects from antagonist joint forces being as low as possible. If, during the movement, there is strong antagonist muscle activity working against the joint driving force (co-contraction) the agonist joint force can be <u>even</u> <u>greater</u> than the calculated, external joint moment (Bryanton & Chu, 2014).

The stiffness of a springboard is easily adjusted by adding or subtracting springs. I mentioned the cable tightness of the uneven bars. However, the natural frequency of a spring floor is roughly twice that of a gymnast (Paine et al., 1996). Paine (1998) showed that slowing the natural frequency of a spring-floor increased take-off velocities. Slowing down the floor made possible a bigger backward somersault tumbling take-off. However, the same competition spring floor is used by both a six-year-old Junior Olympic Level 2 girl and a male Senior Elite. Obviously, these two gymnasts have very different abilities to drive the floor's oscillations. But remember that a spring floor will move at the frequency of a driving force. The skill execution by the gymnast will drive the movement of an elastic gymnastics apparatus. If the gymnast is strong enough, stiff enough, and hitting the floor hard enough, the floor can be driven to oscillate at a frequency approximately half of its natural frequency. If the gymnast is tight enough to suppress the first upwards recoil of the spring floor, the gymnast then can take-off in phase with the second recoil of the floor. However, if the gymnast is not strong enough, the floor will begin to recoil before the gymnast takes-off (Sands et al. 2013). In the other extreme, upon landing the gymnast allows the floor to push their knees up on purpose, absorbs the recoil of the floor, and sticks the landing. Gymnasts driving the deflection of a high bar at much slower frequencies than its natural frequency have been recorded by Naundorf and co-workers, but this means dealing with reaction forces of over six times body weight (Fig. 4. Naundorf, et al., 2019). This is using the bar like a trampoline!

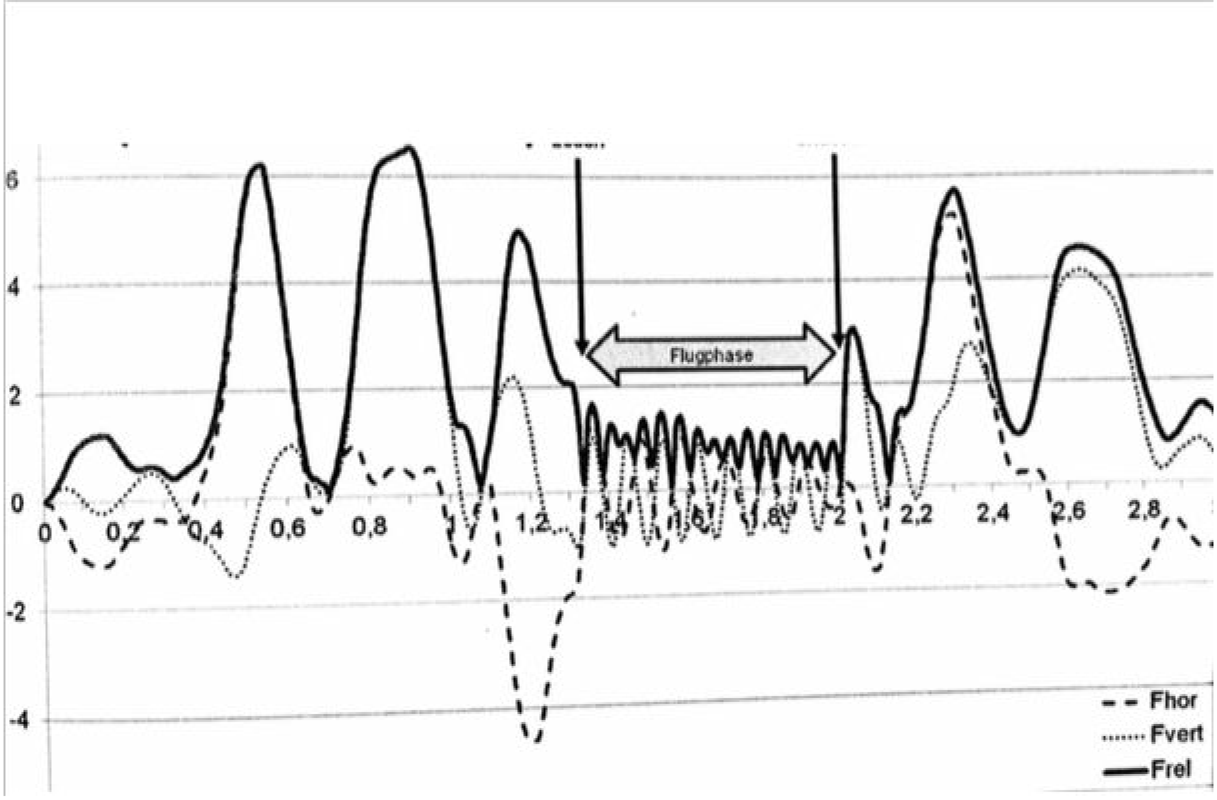


Fig. 4. Force-time curve of a back giant swing preparing a lay-out Tkatchev and catch. Starting on the left at 0, time in seconds runs from left to right in seconds. The vertical bar on the left shows the average force in multiples of body weight. The dashed line is the force exerted by the bar in the horizontal direction (**Fhor**). The dotted line is the force exerted by the bar in the vertical direction (**Fvert**). The solid, black line is the

resultant force relative to gymnast body weight (**Frel**). The bending of the high bar closely follows the force-time curve. There are three high peaks and one lower with high amplitude between elapsed time 0 and 1.3 seconds during one giant swing. The bar is released at elapsed time 1.3 seconds and we then see the high frequency, low amplitude vibration of the unloaded, but lightly damped bar during the airborne phase ("Flugphase"). At elapsed time 2 seconds the bar was caught again, followed by three more large amplitude deflections. From Naundorf, et al., 2019.

Practical Recommendations for Coaches

- Learning to perform the same skills from the widest range of bouncing surfaces is a fundamental part of gymnastics training. This is how the gymnast learns to adjust their body and limb stiffness for best performance. Practice on traditional gymnastics apparatus, but also every kind of trampoline, air floor, pad, bar, etc. In this case, variation is a good in and of itself.
- Co-contraction is an essential ability for a gymnast. For this reason, strength development of muscles on both sides of a joint is important, even if these muscles are not prime movers in gymnastics. An example of a muscle that makes a movement that is <u>not</u> essential in women's gymnastics, bending the elbow, but is important in co-contraction, would be the biceps brachii. Co-contraction is an essential mechanism of tightness.
- Maximal strength is essential if the gymnast is going to successfully interact with modern gymnastics equipment. In particular, ankle and wrist strength is important because these are the ends of the kinematic chains that transmit force to the apparatus (end-point strength; Zatsiorsky, 2002). Maximal strength is difficult to improve with body weight exercise or skill repetition, with the exception of the still rings, and much more efficient with proven weight lifting exercises.
- Improving maximal isometric and eccentric strength must be task specific. In other words, only the muscles that actually work will get stronger. The adaptations to the training will be specific to load, velocity of movement, skill, and number of repetitions. The exercises must also change over time or they will lose their effects; therefore periodizing the training is important.
- The exceptionally high forces that must be resisted for the gymnast to stay tight do not last very long. They can be anticipated by having the gymnast tighten up <u>before</u> these high forces arise. However, the ability to tighten up quickly and with great force is nevertheless a necessary gymnastics ability.

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