An Analysis of the Kinetic Chain Model In Forehand Drive

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ABSTRACT

In the following analysis: a) Critical Force Maximization (CFM) concept is presented, b) Double Kinetic Chain (DKC) model is proposed, c) a new approach for the role of the wrist is presented.

INTRODUCTION

Episteme starts with the abstract principle and applies it, as in the standard mathematical way, which is pretty much what one is obliged to abide by if one is to use mathematics at all and be making logical sense; this is in direct contrast to science, where researchers' models, albeit "mathematical", are made the other way around, i.e. from observations by measuring variables, this being a serious logical deviation. Therefore, one may read scientific articles stating e.g. "Male and female players should be trained to develop the kinematics measured in this study in order to produce effective high-velocity serves"[1], or come across books and chapters such as the "Biomechanics of striking and kicking"[2]. Measuring (e.g. indubitably extremely skilled youngsters) and presenting recorded data as a model is analogous to begging the question; models should always be constructed *a priori*, *predicting* outcomes, and not *accommodating* observations.

However, merely recording kinematic data is different from understanding why they show up this way. This is because theory, as in kinematic laws even, always precedes experiments (there cannot be "theory-independent" experiments). Moreover, theories cannot be confirmed through experiments. Having these in mind, a purely theoretical model for Forehand Drive (FD) is presented, possibly generalizable (in principle) to other shots (or other similar movements). An outcome of the following analysis is that, against prevalent approaches, it aspires to question the use of wrist in FD.

BACKGROUND

Basic Motion Segments (BMS) are the simplest movements that can be studied separately. One-unit kinetic chains (UKC, where BMS's achieve maximum velocity simultaneously) have a definite advantage over uncoordinated ones[3]. So do Serial Kinetic Chains (SKC, where BMS's are coordinated to work serially) over UKC. In SKC's an adjacent segment initiates movement as soon as it has done the following:

1. received the full amount of kinetic energy from the preceding segment,
2. maximally contributed in the increase of the energy it received. If a segment cannot contribute to the increase of energy (e.g. the wrist), it must not be a separate part of the SKC.

Moreover, the subsequent segment *just starts* (boundary condition) its active acceleration phase as soon as it has enough dynamic energy stored in order to overcome its own inertial momentum. Thus, the more rapid the movement and the utilization of the kinetic chain, the higher the inertial momentum is and the more elastic energy is stored before any movement takes place. For example, the differentiation of hip and trunk rotation has been found to be an important force-contributor in mature throwing, accounting for about 40 to 50% of ball speed in skilled throwers[4]. This is also the reason why strokes such as the FD – but not the serve – should not have over-accelerated internal segments, as extensive pre-stretches hinder coordination with the ball and hence impair temporal (translated into spatial) accuracy.

Distinct muscles of the upper body may seldom assist in the further increase of the initial production of kinetic energy from the initial segments (usually the most powerful ones, the legs). Moreover, production of (active) muscle force is only possible as soon as the muscle reaches its normal length and at low speeds (*Figure 1*). It remains doubtful, however, that subsequent segments, being weaker, may add to the kinetic energy they have received, rather than merely convert the existing energy to more speed – which, anyway, is the *desideratum*. This is the rationale behind the Stretch-Shorten-Cycle (SSC). Due to their viscoelastic properties, muscles and tendons increase in stiffness with increasing stretch rates (e.g. see right graph in figure 1 – cf[5,6]). SSC is why seemingly impossible throws are achieved in sports like sphere-throw by very young individuals. The utilization of the kinetic chain is all about the timing of the stretch-shortening cycles of different segments and strength alterations (synchronizing the kinetic chain so that no energy is lost), yet not strength alone.

Paradoxically, the much desired velocity of any segment prohibits it from further developing any significant amount of power[7]. The faster a muscle contracts (or – equally – the faster the limb/segment moves), the less tension its muscle-fibers are able to produce, as actin and myosin filaments are not given enough time to form the maximum possible number of cross-bridges or to contract simultaneously – or both – see *Figure 2*.

Figure 1 Length-tension relationship for the whole muscle contraction (Adapted from Baumann 1996 p.91)

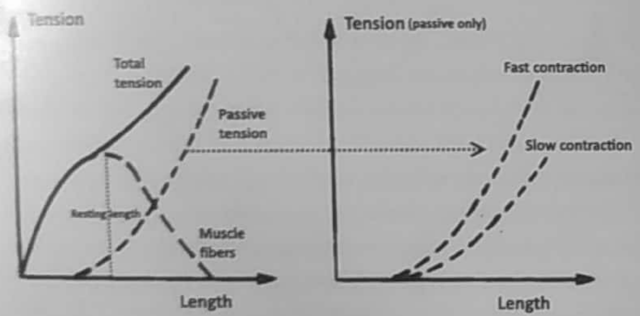
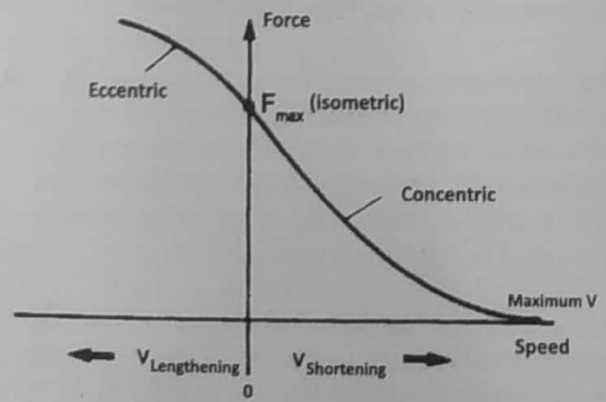


Figure 2 Force-velocity relation (Adapted from[8]).



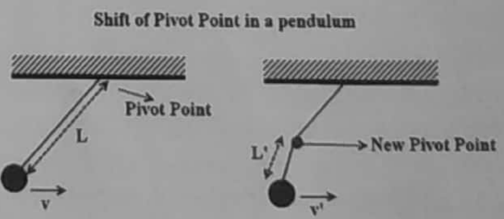
This explains why in UKC (or in mixed chains) some segments, not the ones powerful enough, are used isometrically, not taking part in a SKC as separate segments. Muscles working in multi-segmented chains are in a poor position towards exerting the force they would in ideal cases (like when executing the same movement in the gym slowly).

We often take leg-work for granted and we underestimate the workload performed from the initial segments of a SKC. We have all heard tennis coaches shouting *"faster hand!"*. In spite of the fact that expecting the hand alone to create enough kinetic energy is impossible in the first place, it is important to recognize that, even if a hand may seem impressive because it is fast and… it holds the racquet, the legs or the hips have a much bigger mass to move and, therefore, a much bigger inertial momentum to overcome (more than 100 times – cf[4]). Remember to think of acceleration as the *change* of velocity. It is suggested that the trainer would not be able to directly observe acceleration itself, but rather, its results, after a maximum acceleration period. But a "fast hand" will be the result of very different circumstances that are mainly related to the period before the hand has actually moved. Indeed, the very opposite thing occurs, *deceleration* of body parts causes higher velocities in subsequent segments. This is best explained by the whip-effect.

THE WHIP EFFECT

In the whip effect, acceleration of the suspended weight of pendulum swinging free from a pivot is achieved when the length of its non-elastic and weightless thread is reduced, or equally, finds an obstacle and shortens its "L" length; in other words, there is a shift of the pivot point towards the weight (*Figure 3*).

Figure 3 The whip-effect.



That can be shown in the following idealized pendulum equation

Eq. 1

$$T=2\pi\sqrt{\left(\frac{L}{g}\right)}$$

Eq. 2

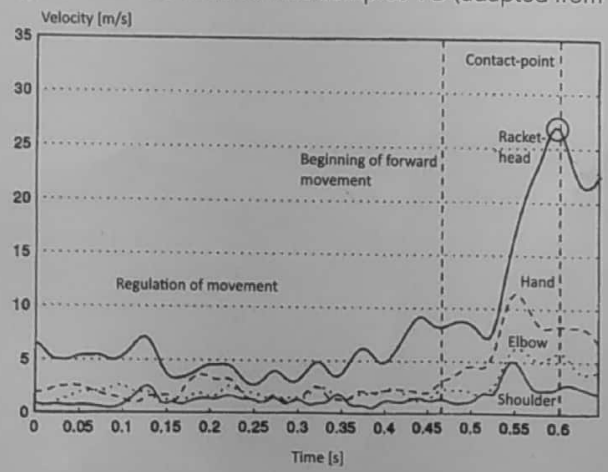
$L\downarrow \Rightarrow T\downarrow \Rightarrow V\uparrow$ (since $V=S/t$), when $T\downarrow \Rightarrow t\downarrow \Rightarrow V\uparrow$)

...or via a d'Alembert force acting on the weight after the said shift of the pivot point. This is very important in the SKC model, because what it really means is that a player still has one more last-moment resource to recruit: their antagonists (after both active and passive tension from agonist muscles has maximally contributed) .

Antagonists, normally recruited only to stabilize the joints, now play a critical role in actively decelerating a segment so that the pivot point will be shifted forward and the subsequent segment will accelerate. That is another benefit of SKC. The whip effect is more evident in the interaction of segments that are towards the end of the kinetic chain, as they have much lower mass and – therefore – much higher speed. In tennis, the whip effect is more evident in the pectoralis/biceps brachii system and in the upper arm segment connected with the elbow joint. The antagonist muscles responsible for the whip effect are the triceps brachii and the posterior deltoids, which together decelerate the elbow. The elbow stops its movement *almost exactly* at ball contact (a boundary condition) to induce the whip effect and further accelerate the forearm/racket system.

Another crucial characteristic of the body, at least when we see it as a pendulum system with a *partly* forward progressing pivot point (partly because there is another pivot point – the initial one which was on the front foot – that remains active), is that the body is not non-elastic (the thread of a theoretical pendulum in non-elastic). It actually alters its own length (shortens at impact) acting as a spring further affecting *L* and further accelerating the movement. For this to occur, full relaxation of the musculature is required during the backswing phase. Not until the forward-swing should there be active recruitment of the agonist muscles, and, exactly prior to ball-contact, activation of antagonist muscles should take place, as described earlier.

Figure 4 Kinetic chain of Pete Sampras' FD (adapted from[9]).



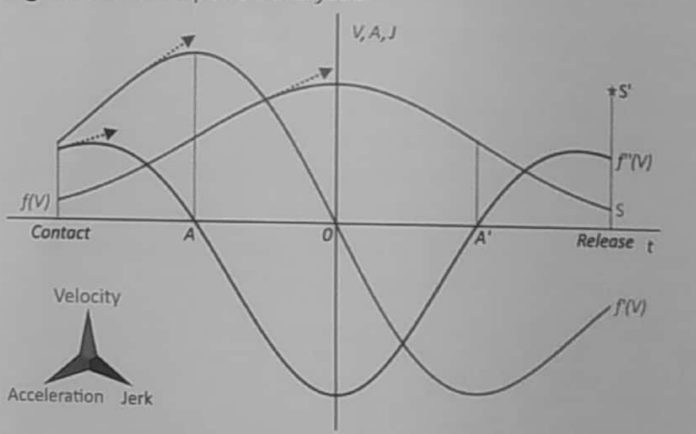
† Also known as the Force-Time Principle: *The time available for force application is as important as the size of the forces used to create or modify movement.*

KINETIC CHAIN ANALYSIS

Having as a starting point Sampras's F.D. kinetic chain (*Figure 4*), let us idealize and elaborate on the former a bit more. A part of the graph (circled) denoting contact with the ball will be idealized, in accordance with the epistemonic method: *interpretation* is the process of name-giving to meaningless archetypes.

Figure 5 represents the contact period, which, obviously is not a "point", with a duration of many *ms*, translatable into several *cm* of movement of the racket-hand system together *with* the ball. Indeed, everything a player does, in the literal sense, has the optimal behaviour of their racket at contact period as a goal. The vector Impulse (*J*) is applied force (*F*) × time (t) ($J=F\Delta t$). Exactly because Δt (the period) exists, *F* must be as big as possible for this period in order for *J* to be maximum†. The conventions made were: the curve is symmetric, the X-axis is greatly enlarged and jerk graph is adapted to fit the graph; the said conventions do not compromise our final conclusions.

Figure 5 Contact period analysed.



Explanation. From t=*Contact* till t=A the racket maintains a positive jerk, i.e. it still accelerates. Exactly at the *Contact*, the applicable force is zero and it gradually increases to its peak when the strings are maximally stretched (half-period/alternation), to decrease to zero once again (at *Release*). The first derivative of *velocity* is *acceleration* and the second derivative of velocity is *jerk*, which is acceleration's first derivative. Derivatives represent *rate of change*. Here: $f(V)=e^{-2V^2}$, $f'(V)=-4e^{(-2x2)}x$, and $f''(V)=4e^{(-2x2)}(4x^2-1)$.

If no ball contact has taken place, it is evident that the velocity of the racket would further increase (doted blue arrow). The same applies to the other two curves. Even if there were no ball contact, at some point (before range of motion becomes the limiting factor), the system would start to decelerate, as the musculature starts to become unable to sustain its own power output.

A biomechanically sound technique would allow the racket to keep accelerating almost as if no contact had taken place (*S'*). The closer S to S' is, the more competent the player.

Distance $S-S'$ represents "lost acceleration". Ideally one should hit as if there were no ball: $\lim_{S \to S'} f(S) = f(S')$. When the ball leaves the strings, the racket should have just finished accelerating. Acceleration is the area between $f''(V)$ and t, i.e. the integral of $f''(V)$ from Contact to Release. $J = F\Delta t = m\Delta V$, and $F = ma$ (mass is constant). The closer S to S' is, the greater the jerk – this being the desideratum. *Note*: due to ball's momentum, S' is not likely to coincide with S, but the more force an individual is able to apply, the closer it will get.

- Conclusion: F (force) must be maximized during the whole collision interval time (in contrast to just maximizing force instantaneously at an allegedly specific point in time).
- This maximization of force during the whole duration of contact is what we call Critical Force Maximization (CFM).

APPLICATIONS

The sum [Kinetic energy] + [Dynamic energy] = [Mechanical Energy] is always stable. Like a pole vaulter, obliged to use the optimum combination of speed and dynamic energy (as elastic deformation of the pole), a tennis player will experience a release feeling only when he has permitted his racket to find the ball forward enough so that all dynamic energy would have just been transformed into kinetic energy for the ball contact – but not sooner or later. *Too early* a contact means that potential stored in the athlete's body as dynamic energy is wasted; of course, too late means that contact is made while the racket is decelerating. In other words, *time precision at contact affords the delivery of greater impulse to the ball.*

In recorded measurements, moments before contact, there is a period of zero acceleration. This is an automatic motor adaptation to diminish mistakes due to the always present biases (bad perception, bad/unexpected ball bounces etc.). This has been observed in many top professional players in previous years[10]. It should be expected that a better player is able to keep accelerating closer and closer to contact point, while maintaining directionality of the racket face, or else not all of the kinetic energy will be transformed into acceleration (speed) in the desired direction. The timing of the hit must be both precise and error-free, so that the mean direction of the racket face is towards the desired direction. *Note*: the direction is usually not towards the target, as almost always there is an angle between incoming and outgoing ball.

The racket face will continue to point in the direction of the desired direction, as long as the compensating movements of hand pronation and internal rotation take place. However, if the wrist is to be used as the pivot point via wrist flexion, it will result in a change of direction of the racket face.

Examining the wrist more closely. This analysis may be applied to any other part of the kinetic chain, where, instead of energy transfer to the ball, there is energy transfer to the next segment. Wrist flexion is the only possible movement a wrist may perform, being already fully extended in the backswing phase (*cf.* Force-Time and Range of Motion biomechanical principles, see[6]). Because of the whip-effect and other considerations, if the wrist engages, it would terminate the accelerating period of previous segments a fraction of time earlier. Moreover, the racket's acceleration is the result of a powerful internal rotation of the upper arm which, for example, in the serve contributes ~40% of speed vs. ~5% by wrist flexion[11]. Could we then use internal rotation and wrist flexion simultaneously? The simultaneous recruitment of a second muscle group would decrease the power of the first one – a classic effect found in literature[12,13].

Impulse required during contact is well beyond the capacity of the wrist. If, for example, wrist flexors are able to exert under favorable conditions, say, 30 N of force, they can perform much worse in a condition where they flex rapidly (*Figure 2*). Thus, they can only exert a very small impulse during the contact period – a fraction of the energy they have received via the kinetic chain.

Likewise, in a simpler manner, since $J = 2mV$ (elastic collision), if the ball weighs 0.060 kg and travels at 30m/s, impulse is 1.8 N.sec (or *Kg m/s*), thus the force needed would be $F_{mean} = J/\Delta t$ (Δt= approx. 0.008 sec), F_{mean}=225 N. Moreover, it is arguable that, rather than accelerating the ball, one accelerates the entire racket-lower-arm system. In this case, mass would be approximately 2 kg and velocity 30 m/s. Then $J = mV$ (and not $2mV$), => J=60 N.sec and likewise, F_{mean}=7.500 N. Again, one cannot see how the wrist may supply that amount of force: for example, wrist flexion strength capacity (always less than extension's capacity) varies between 40 N (females, 75° extension) to 105 N (males, 90° flexion angle)[14].

Note, in addition to the aforementioned that the ball is hit not by the mass of the racket alone but by the racket-lower-arm system because racket-lower arm inertial system has significantly more mass than racket alone. This is achieved by maximizing grip force at impact – the same as in punching in martial arts. It is impossible to move (flex) a fully stiff wrist joint (let alone flex it rapidly). All agonists and antagonists are fully activated. By contrast, hand pronation can be freely performed as it is an elbow movement.

Summing up, contrary to the prevalent approach, here are the major reasons why wrist flexion should *not* be used. 1) The whip effect necessitates the former segment (forearm) to stop moving. 2) If wrist flexion was utilized, contact with the ball would take place sideways, not in front of the body, and the injury risk for the wrist would be higher. 3) If the flexing wrist was the pivot point, it would give the racket face a rapidly changing direction, making it hard for the player to be consistently accurate. 4) Wrist utilization would further increase freedom degrees, making coordination more difficult (see next section). 5) Wrist flexion simultaneously used with pronation and internal rotation would make maximal exertion of the other agonists impossible, apart from cancelling the whip effect.

THE DOUBLE KINETIC CHAIN

Both beginners and professionals, subject to coordination and time-restriction problems respectively, may find the utilization of a SKC in FD problematic. The problem may be reduced to an analysing of Degrees Of Freedom (DOF's) corresponding to the number of kinematic measurements needed to completely describe the position of an object. A simple way to reduce DOF's is to reduce (freeze) segments. In play, there are some very popular ways to reduce DOF's, namely open-stance (eliminating the very first segments of the kinetic chain) or the elimination of the pre-stretch of chest musculature (thus eliminating one of the last segments).

Playing tennis is full of surprises. Thus, it is often necessary for the player to use manipulations and thus *deliberately* reduce the segments. Therefore, in many cases, it seems that reduction of DOF's is a "necessary evil". However, here the author will argue that reducing the DOF's in forehand is also the optimal way to hit the ball.

A SKC, used in tennis serve, javelin or discus throw is optimal because it maximizes speed. In groundstrokes, however, where there is a fast incoming ball, one needs to *resist* it first before one is able to redirect it. A *double kinetic chain* is proposed here for this: upper body moving in a SKC, coordinated to reach contact with the ball at the same time when the weight-transfer has just finished. A very similar manipulation is used to control the Japanese samurai sword and bokken: the end of cut and the weight-transfer are perfectly coordinated to finish simultaneously. Cutting is done with a SKC (upper body), which, in the end, works in parallel (UKC) with the lower body. CFM h ere is achieved by the accuracy in the coordination of the two kinetic chains: one serial and one one-unit. In the kinetic chain graphs of tennis strokes, the double kinetic chain is not visible, as the transfer of weight is not depicted (only the velocities of shoulder, elbow, hand and racket are recorded).

If one treats the racket-arm and the legs as two independent system††, then one may apply the concept of *forced oscillations*. The racket-arm system then is oscillating with a given amplitude and a given frequency. In this case, proper timing between the parts will produce resonance. The racket-arm system, when approaching the contact point, subject to the constraints discussed in the previous pages, may be considered as the independent physical pendulum system, connected with the rest of the body through a spring. It can be shown that, if a *driving force* (from the legs) of the same frequency acts upon this system, the system will resonate, i.e. the amplitude will reach its maximum value.

CONCLUSION

Some main points have been presented in regard to the theoretical part of the model for a FD; a final model should include an analysis of aerodynamics of a travelling tennis ball in combination to an analysis of torques on the ball at contact point. How these parts actually translate into a forehand drive would be the final synthesis, after the mechanism has been fully described . Furthermore, shedding more light on the applied part of the Double Kinetic Chain model, i.e. constructing (recording) more holistic, accurate and multi-factor kinetic chain graphs, would improve our understanding.

- Merely recording kinematic data is different from understanding why they are this way
- Maximization of force during the whole duration of contact is called Critical Force Maximization (CFM). It is the most crucial element to understand power production in the double kinetic chain model.
- Wrist utilization is discouraged.
- Double Kinetic Chain is the proposed model for the maximization of CFM

†† Independence here is meant in the sense of the internal inter-relationship of the parts of a system that are sufficiently free to exert influence upon each other.

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