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How to use the Elasticity of a Badminton Racket to increase its Speed by 80%

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1.Introduction

Badminton rackets generate the highest particle velocities among all sports (137 m.s^{-1}) (Cohen, 2014). Here, we investigate the role of elasticity on this particularity. Racket stiffness and mass properties likely influence the impact and restitution coefficient (Montagny 2003). In the present study, we investigatethe difference of velocity obtained with or without the elasticity of the racket in two different experiments. The first one allows to assess the flexible/rigid velocity ratio in a linear motion using a mechanical actuator. The second one aims to compare this result with human motions.

2. Methods

2.1 Experiment 1: racket deflection with actuator

To understand the difference of velocity between handle and head of the racket obtained by deflection, we firstly constructed a mechanical actuator (Figure 1a) which allows to accelerate the handle of a racket (Carlton x90; 675 mm; 86 g). This experiment was designed to study the mechanical behaviour of the racket in an ideal case. The pulsation of the racket, defined as the frequency at which it naturally oscillates,isω_0 = 84 rad.s^{-1}.Actuator (Power Rod PRA 2510) generated a linear motion of 22 cm of the racket, which reached a maximal velocity v_A = 3.3 m.s^{-1} in a time ranging between 60 ms (corresponding to a maximal acceleration $\gamma \approx 50$ m.s^{-2}) and 700 ms. To increase racket deflection, a weight of 88 g was eventually added on the racket head (thus reducing $\omega_0$to 37 rad.s^{-1}).We extracted the dynamics of the racket from the movies obtained with a high speed camera Phantom V9 acquiring at 250 fps and measured the maximal velocities of the handle (v_A) and the head (v_B).

2.2Experiment 2: racket deflection with human

In a second time, to understand how players take advantage of the elastic effect of the racket, 24 healthy volunteers (experts and novices) free of injury (174.5 ± 8.7 cm; 70.7 ± 9.9 kg, 7 years of experience) participated in this study. The experimentwas approved by the local ethical committee. The same racket as for actuator experiments wasused by all subjects. Participants were instructed to fix the shoulder and the elbow at 90° flexion angle in the sagittal plane in a standing position. Then, they extended the forearm to give the higher velocity as possible to the racket head (figure 2b).

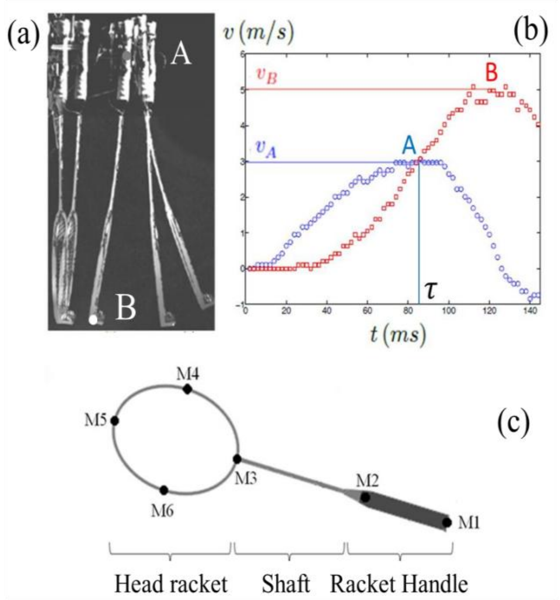

Figure 1: (a) Chronophotography of the racket accelerated by actuator with a weight of 88g. The time interval between two images is 40 ms. (b) Evolutions of velocities of handle (blue circles) and head (red squares) with time.(c) Illustration of shape and marker placement.

Six reflective markers were affixed on the racket (Figure 1c). To calculate the joint positions, a 3D model (Plug-In Gait Marker Set, Vicon Peak) was used. The reflective markers placed on the racket weighing 1.2-2.4g each, increased total mass by 12.4g (14% of the racket weight).As the human movement is not linear like the actuator motion; we have to compare the racket head velocity to a virtual stiff racket velocity, instead of the handle velocity. We built (Matlab R13a)a virtual marker (M5')using the two markers on the racket handle (M1 and M2). This new marker is at the same position as M5 when the racket is not deflected, but stays aligned with the handle when it is accelerated, allowing to create a virtual stiff racket.A one-way Anova is used to assess

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the difference between the stiff virtual racket and the real flexible racket with $p < 0.05$ and the power (1-β).

3. Results and discussion

3.1 Racket deflection with actuator

We observe in figure 1b that when the handle is accelerated, the head moves with a delay, resulting in a deflection of the shaft and the maximal velocity reached by the head is greater than the maximal velocity of the handle, due to the elastic deformations. Racket deflexion increases with the acceleration it undergoes. We quantify the acceleration of the racket with the pulsation of the handle motion, defined as the inverse of time needed to reach the maximal velocity ($\omega = \pi/\tau$). One observes on figure 2a that for small acceleration the velocity ratio (v_B/v_A) is equal to one and increases with acceleration until a maximum of 1.7 for a pulsation $\omega = 1.2\ \omega_0$.

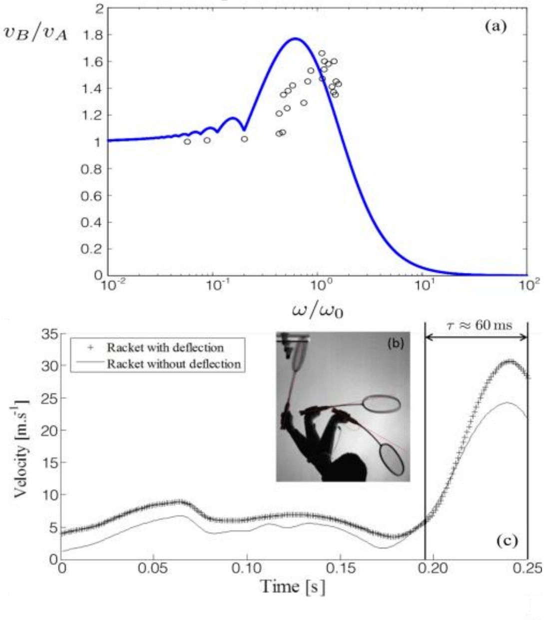

Figure 2: (a) Ratio of head and handle maximal velocities (v_B/v_A) in function of pulsations ratio (ω/ω_0), for actuator experiments (black circles) and predicted by the model (blue line). (b) Velocity of racket head (M5)with (+) and without deflection (M5') (solid line). (c) Chronophotography of the badminton stroke.

To understand these features, we model the racket as a spring with a stiffness (k) and a mass (m = 86 g).The second law of Newton provides an expression of the velocity ratio (v_B/v_A)in function of the pulsation ratio (ω/ω_0):

$$\frac{v_B}{v_A} = \frac{1}{1-\omega/\omega_0} \sin \frac{\omega/\omega_0}{1+\omega/\omega_0} \qquad (1)$$

Equation (1) is plotted on figure 2a and predicts that the optimal ratio of maximal velocity is 1.8 obtained for $\omega = 0.6\ \omega_0$. It shows a rather good agreement with experimental points, especially on the value of the maximum (≈ 1.8). The shift in pulsations can be explained by two main reasons. First the fixation of the racket handle is not completely rigid for high accelerations, and it results in a decrease of the stiffness (k). Hence $\omega_0 \propto k/m$ decreases and the ratio ω/ω_0 increases. Moreover the equation (1) is derived for a sinusoidal expression of the handle motion with time, whereas we can observe on figure 1b that it is not the case experimentally. And we observe numerically that a change of shape of the handle velocity curve entails a shift of the maximum of the velocity ratio.

3.2Racket deflection with human motion

In these experiments we comparethe head velocities ofvirtual rigid racket and flexible racket. Figure 2c shows an example of the dynamics obtained for a deflection of 12 cm and a maximal acceleration of 77m.s^{-2}. The maximal velocity obtained with the elasticity of the flexible racket is 24% higher than the rigid one ($p<0.001$; 1-β = 0.99).The elastic energy stored in racket deflection can contribute significantly to racket head velocity. A totally stiff racket produce the same velocity at handle and head (Kwan et al. 2008). A greater flexibility increases the capacity of the racket to store and release more strain energy. Moreover, the typical time during which the player accelerates the racket head is 60ms, corresponding to a pulsation ratio $\omega/\omega_0 = 0.62$. This value is very close to the optimal value predicted by the model, about 0.6 (figure 2a).

4. Conclusions

This study shows that players take advantage of the elastic effect of shaft deflection to increase racket head velocity. We measured a velocity gain of 25% and predicted it could reach 80%. The racket restitution coefficient is highly affected by its stiffness and mass properties and has to be adapted to player abilities. Moreover, experts have better used the racket elasticity than novices. Indeed the time needed to reach the maximal velocity has to fit the racket oscillation time. Finally this study suggests that the temporal pattern of the acceleration is a key point to optimize the elastic effect and has to be practised by players in order to break the velocity record.

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