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Control of ball-racket interactions in rhythmic propulsion of elastic and non-elastic balls

Received: 14 February 2002 / Accepted: 18 October 2002 / Published online: 16 January 2003
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Abstract Ball-racket interactions were investigated in a task where participants propelled a ball rhythmically into the air. The study contrasted two ball-racket conditions: (1) an elastic impact where the ball was able to rebound due to the elasticity of the colliding objects and participants bounced the ball, and (2) a non-elastic impact where the coefficient of restitution was zero and the ball did not rebound such that the participants had to throw the ball. The goal of the study was to contrast the situations where haptic information about the ball-racket interactions is either secondary (elastic bouncing) or becomes a primary factor for control (non-elastic propulsion). In the elastic condition, the performers controlled the parameters for ball-racket contact prior to contact: In agreement with the criteria for dynamical stability defined by a model, racket accelerations immediately before the contacts were negative, racket positions and velocities at the instant of the initial contact correlated negatively, contact durations were short (30 ± 9 ms), and during the collision interval racket velocity and acceleration decreased monotonically. In the non-elastic condition, the parameters of ball release were primarily controlled during the collision phase: Racket accelerations before contact were positive, racket positions and velocities at initial contact showed weak correlations, and the contact intervals were significantly longer (116 ± 15 ms) with a clear segmentation into two segments. Negative correlations were observed between the integrals of the velocity and acceleration computed over the two consecutive segments, giving evidence that in the non-elastic condition the CNS is able to introduce corrections during the very short collision interval. The results are discussed with respect to physiological mechanisms of movement corrections available during such short time intervals.

Keywords Dynamical stability · Haptic perception · Force control · Interceptive skills

Introduction

Collisions play an important role in our daily lives and in many sports activities. Numerous ball sports have been invented where different ball handling techniques and their special demands present the core challenge of the game. Examples are tennis and other racket sports where ball-racket collisions are short, similar to kicking a football in soccer. Slightly prolonged contacts are required in the skill of setting a volleyball, or in dribbling a basketball. Similarly, such controlled contacts are central for playing the piano. Striking a piano key is a controlled action where the finger touches the key for a more or less prolonged time interval with different release velocities in order to produce different tonal qualities. What distinguishes these finger-key, ball-hand, or ball-racket contacts is their contact interval from being very short to more prolonged and “controlled.” Expressed in mechanical terms, they differ in their elastic nature of the contact.

In a series of previous studies we investigated a task that consisted of the repeated bouncing of a ball in the air with a tennis racket. This task had to be performed rhythmically over approximately 40 s and a consistent ball amplitude had to be achieved. The ball-racket contact was elastic and the contact durations were short, in the order of 30 ms. The question of these studies was how a stable rhythmic movement regime was achieved (Schaal et al. 1996; Sternad et al. 2000, 2001). Specifically, we examined the dynamical stability of the task performance defined as the regime where small perturbations die out without additional compensatory corrections. To this end, a kinematic model for the ball-racket system was developed whose system of difference equations was subjected to stability analyses. The few assumptions entering into the model equations were periodicity of racket trajectories, ballistic flight of the ball, and elastic

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impact between ball and racket. The latter property implied that there was a constant energy loss at each contact and, importantly, that the contact was assumed to be instantaneous, i.e., uncontrolled. Stability analyses of the model revealed that a negative acceleration of the racket at the moment of ball contact was the central criterion for establishing a dynamically stable ball bouncing regime. This meant that prior to contacting the ball, the racket movement had to decelerate, with optimal values between -5 and -2 m/s². Hitting the ball with negative acceleration of the racket before the collision was argued to be a very parsimonious control strategy as it did not require explicit error compensation.

A series of experiments confirmed that human actors indeed hit the ball with negative racket accelerations in the predicted range when they attempted to obtain consistent sequential bounces of the ball. That racket acceleration was an essential variable to which human actors attuned to was further supported in different experimental set-ups and task variation (Katsumata 2002).

Given that actors are apparently sensitive to this racket acceleration at contact, an associated question was directed to the kind of perceptual information that guided this attunement (Sternad et al. 2001). The role of perceptual information was studied by excluding in turn visual and haptic information about the contact.¹ To exclude information about the ball contact, a telerobotic device was used where performers moved a racket rhythmically, but a second computer-controlled racket actually bounced the ball. Hence, no information about the ball contact was transferred to the hand and arm, while kinesthetic information about the arm movements remained unchanged. Analyses of the racket accelerations at contact showed that haptic contact information was more critical than visual information in obtaining dynamical stability, even though the contact duration is extremely short compared to the continuous availability of visual information. When performing the task with eyes closed, but with contact information available, performance remained stable.² On the contrary, when the performer was deprived of haptic information about the contact, but could see the continuous ball trajectory, the contacts showed more positive racket accelerations. Within the modeling framework, this solution was unstable and required continuous control and error compensation to offset small errors. This result highlighted that despite the short duration of accessible information (30 ms) the contact appeared to provide more salient kinetic information about stable ball control than the continuous kinematic information.

With respect to the previous model-driven assumptions and experiments, it was interesting that the contact

interval was of apparent significance, in contrast to the mathematical assumption of an instantaneous impact. Therefore, the present study aims to prolong this contact interval further to investigate a case that explicitly exceeds the assumptions of the model. While previous results have given support to the hypothesis that actors control the ball by exploiting dynamical stability, which, in principle, does not require compensatory regulation, the present study will modify the task such that regulatory control is expected to play a major role. The present task is modified such that the contact is prolonged to allow haptic information to become a major source of information. This is obtained by creating a non-elastic ball-racket condition. When energy is lost during a collision, energy has to be added to the system to project the ball to a given target. This means that more control is required to maintain performance. The hypothesis is that the longer the contact and the more energy is lost, the more control and contribution from perceptual information will occur.

The elasticity of the contact is described by the coefficient of restitution (CR), which is defined as the ratio of relative velocity of two colliding bodies just after the collision to the one just before the collision. A perfectly elastic impact with no energy loss has a CR of 1. The other extreme occurs if the kinetic energy is completely dissipated and the CR is zero, i.e., it is a non-elastic collision. When hitting a ball with a racket with a CR <1 , additional energy must be injected into the ball to project it to the required height. Two sources of energy are used: One portion of the energy comes from the kinetic energy of the racket-arm system at the initial moment of contact. The second source is work done by the active muscles during the contact. If the first source of energy dominates, the ball-performer interaction is classified as impact-like; while in the second case the interaction is throwing-like (Tsaousidis and Zatsiorsky 1996). The reason behind this classification is that, in throwing, the ball energy increases due to the muscle work performed *during* the contact with the ball; while in “pure” impacts, e.g., in golf hitting, the ball energy is due to the momentum and kinetic energy of the club *before* the contact.

The objective of this study is to investigate the control mechanisms used in ball-racket collisions with elastic and non-elastic balls. It is hypothesized that people adjust to the elastic properties of the ball by employing different control strategies, either exploiting dynamical stability, or using a perception-based ball propulsion. In the following experiment subjects propelled a ball repeatedly in the air and the ball amplitude and the period between ball contacts was prescribed by a metronome to three different periods, i.e., the task was rhythmic. We will examine the characteristics of the racket movement before and during the contact.

¹ The term “haptic” is used for the perceptual information derived from and about the ball contact. This involves sensory information from mechanoreceptors in the skin, and receptors in joints and muscles (proprioception).

² Note that the ball could not be lost, even with eyes closed, as the ball was constrained to a linear path.

Materials and methods

Participants

Twelve participants from the University population volunteered for the experiment. Three of them were faculty members, four were from the undergraduate student population and five were from the graduate student population of the Department of Kinesiology at the Pennsylvania State University. All of them reported that they were right-handed and none had any arm injuries in the past. After the experimenter had explained the purpose and procedure of the experiment, each participant signed the informed consent form in accordance with the Regulatory Compliance Office of the University. Six participants were assigned to perform in the elastic condition (two females and four males, average age 28.8 years). The other six participants performed in the no elastic bouncing condition (one female and five males, average age 26.7 years).

Apparatus

The task was performed with a racket as regularly used in racket ball. For the elastic bouncing condition, a sponge ball of the same size as a tennis ball was used. The coefficient of restitution for the given ball stiffness and racket string tension was determined empirically. In ten trials the ball was dropped from a standard height onto the stationary racket. The ball velocity of the sample directly before contact and directly after the contact was used to determine the energy loss at contact, that is the coefficient of restitution (CR). For the elastic case the average value was 0.52. This value is close to the required CR of new tennis balls, 0.55. For the non-elastic bouncing condition, a bean bag of tennis ball size and a weight of 75 g were used. A light wooden board (5 mm thick) was fixed on the racket frame as a hitting surface. Lightweight material was chosen so that the weight of the racket and ball were small to prevent participants from fatigue. The value of the CR was empirically determined as in the elastic case and did not differ significantly from zero.

To record vertical displacement data of the racket a thin string was tied to the racket surface, approximately at the center of percussion. The other end of the string was attached to a wheel whose axis of rotation was fixed to a metal floor piece (0.41×0.18×0.02 m) weighing 30 kg (Fig. 1). An upward racket movement rotated the wheel and uncoiled the string from the wheel. A spring provided moderate resistance but ensured that the string remained tight. The spring also ensured that in downward movements the string was wound around the wheel again. A ten-turn potentiometer was attached to the wheel's axle to measure the rotations of the wheel, which were converted into vertical displacement of the racket. The stiffness of the spring was adjusted so as to prevent the string from becoming slack during the downward racket movement, but not to produce too much resistance during the upward movements. To measure the vertical acceleration of the racket a uniaxial accelerometer (Coulbourn, PA) was attached at the handle of the racket close to the hitting surface (Fig. 1).

The ball was fixed to one end of a 1.15-m-long tube made of carbon fiber with a diameter of 20 mm and wall thickness of 0.5 mm. The tube was fixed onto a hinge joint on the top of a vertical stanchion (Fig. 1). At the short end of the tube (0.15 m), a weight of 0.20 kg was attached to offset the weight of the long end of the tube. Within ± 30 deg of the rotation of the tube, the vertical movement of the ball could be approximated as linear. A potentiometer was attached to the hinge joint of the tube to measure the angular rotation of the tube.

All analogue data from the two potentiometers and the accelerometer were digitized using a 16-bit A/D board (National Instruments, TX) and sampled at 500 Hz using software developed in LabView (National Instruments, TX). Data of angular rotation from the ball and the racket devices were converted to the vertical displacement of the racket and the ball. By constraining the ball flight to one dimension via the ball's connection to the tube, the

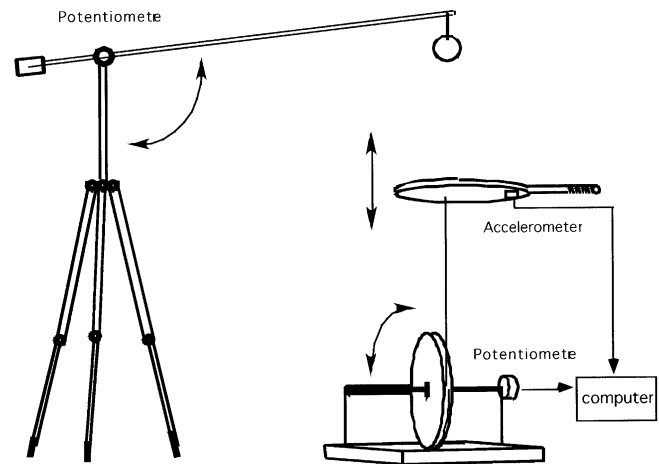


Fig. 1 Experimental apparatus

racket movements were automatically restricted to the same approximately linear dimension. By placing the racket device on the floor right underneath the ball path, the rotation of the wheel corresponded to the vertical displacement of the racket.

Task

Participants were asked to hit the ball with the racket and to maintain this bouncing action for 30 s. To facilitate consistent bouncing periods across all participants in both the elastic and non-elastic bouncing condition, a metronome was used to pace the frequency and thereby also prescribe the ball amplitude. Participants were instructed to synchronize the timing of the collisions with the metronome beeps throughout the entire trial.

Procedure and design

At the beginning of the experiment, participants practiced the task until they got used to the equipment and its constraints. This only took approximately 5–10 min. In addition to the two CR conditions (0.52 in the elastic bouncing and 0 in the non-elastic bouncing), the experiment provided three period conditions: 714 ms, 535 ms, and 417 ms. The reason for the odd numbers of milliseconds was that the metronome specified beats per minute. For each trial, participants started to bounce the ball and tried to synchronize the hitting with the metronome beep. Once they had established a stable bouncing pattern, they sent a cue to the experimenter to begin data collection. The data collection for each trial lasted for 30 s. The CR conditions were presented in blocks to the two groups of participants. The period conditions were presented in completely randomized order. Five trials were conducted for each period condition. The data collection for each CR condition lasted approximately 20 min. Participants could rest their arms between trials whenever they wanted.

Data processing and reduction

The signals collected by the accelerometer provided the basis for determining the onset of the ball-racket contact. The moment of contact was determined as the sample when the signal revealed a marked discontinuous change induced by the collision. Before collision the acceleration signal changed smoothly, while after the first moment of contact the signal started to display marked vibrations. The sample directly before this change was used as the acceleration before contact. To avoid any distortion of this information the signals were not filtered.

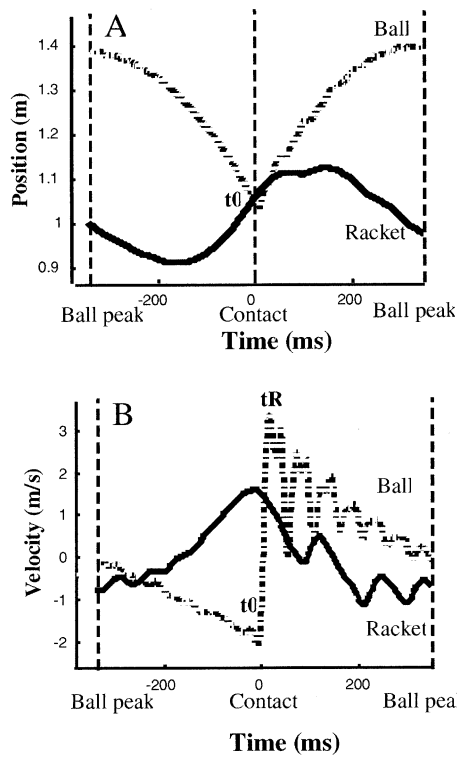


Fig. 2A, B Kinematic profiles of racket and ball during one typical cycle of the bouncing action performed with elastic ball and racket contact. Individual cycles are defined between two subsequent peaks in the ball trajectories. **A** Position of racket and ball. t_0 denotes the time of the initial contact as determined from the accelerometer signal (indicated by the vertical line). **B** Velocity of racket and ball

Filtering the registered signals of the ball's and racket's vertical displacement was a critical issue as the signals contained different frequency content due to the smooth portions of ball and racket trajectories, the discontinuous changes of position at the collisions, the vibrations following the collisions, as well as measurement noise (Figs. 2, 3). The challenge for filtering the data was to cut off the noise without losing precise timing information about the onset and offset of the discrete events at the collision. Using a zero-lag fourth-order Butterworth filter, the best cutoff frequency was 50 Hz. To arrive at this choice of cutoff frequency, we examined the results of filtering the position signal and compared cutoff frequencies in the range between 2.5 Hz to 125 Hz. The criterion for the cutoff was determined by evaluating the velocity signal of the racket trajectory. As shown in Fig. 3B, a characteristic feature of the racket velocity during contact was the initial decrease and a final increase for propelling the ball, especially for CR=0. To maintain this feature, the filtered racket velocities were compared and a trade-off was sought between a smoothing effect and maintaining this critical feature. The velocity of the racket trajectories was obtained by numerical differentiation, and it was filtered again with the same filter and cutoff frequency of 50 Hz. The racket acceleration was obtained by the same differentiation and filtering procedures. For the kinematic analysis of the racket movement, the acceleration obtained by numerical differentiation of the position signal was used. The differentiated signal was better than the accelerometer signal as the latter showed high oscillations during the short interval following the initial contact due to the mechanical design of the measurement device.

Filtering the position data of the ball was more problematic, since the ball's movement direction changed abruptly at the collision and it was crucial to maintain the details of the trajectory

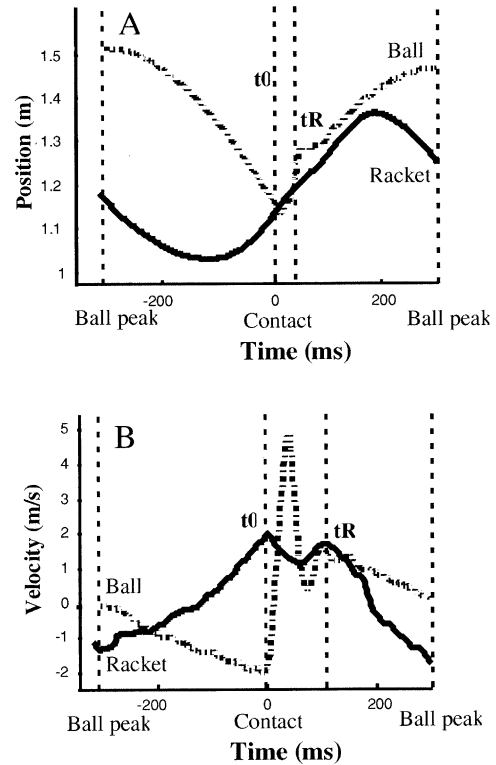


Fig. 3A, B Kinematic profiles of racket and ball during one typical cycle of the bouncing action performed with non-elastic ball and racket contact. Individual cycles are defined between two subsequent peaks in the ball trajectories. **A** Position of racket and ball. t_0 denotes the time of the initial contact as determined from the accelerometer signal (indicated by the first vertical line). t_R denotes the time of ball release as determined from a second velocity peak and indicated by a vertical line. **B** Velocity of racket and ball

directly following the initial contact. Therefore, we chose to segment the ball trajectory into individual cycles to allow a variable determination of filter cutoff frequencies for each cycle. To avoid transient effects at the most critical part of the trajectory, the moment of ball-racket contact, we chose to segment the trajectory at the ball peak positions. Subsequently, each cycle segment was filtered separately and the filter cutoff frequency was determined based on two criteria: First, the moment of ball minimum had to coincide with the moment of abrupt change in the accelerometer signal, which was the best raw signal to determine the time of ball-racket contact. In addition, the second peak in ball velocity, indicating the release point, had to coincide with the velocity peak in the racket velocity signal. Based on these two criteria the optimal cutoff frequency for each cycle segment was determined. Typically, the first and second criteria coincided to yield one optimal cutoff frequency. The mean cutoff frequency across all collisions for all trials was 30 ± 7.5 Hz. Note that the ball trajectories were fluctuating especially after the contact. The ball trajectory after the release was therefore never included in any analyses due to this significant measurement noise. The trajectory segment preceding the racket contact also showed some noise, but across a cycle segment of approximately 1/4–1/2 cycle before racket contact, the slope of the velocity signal was very close to linear, meaning that the effect of gravity was constant. The effect of these fluctuations in the ball trajectory prior to contact on subsequent measures was minimal. The only analysis that used a value of the ball trajectory is the estimation of CR using a ball velocity directly before and after the contact. This analysis gave CR values that were very close to the ones determined under very controlled conditions before the experiment, indirectly confirming that this noise had only little

influence. All other analyses examined the racket trajectory during the contact. As the stiffness of the ball suspension was very small, the fluctuations of the ball were immediately dampened at the contact with the racket and had minimal effect on the racket trajectory.

Kinematic measures

To elucidate the different control strategies the analysis focused on parameters of the collision interval. As illustrated in Figs. 2 and 3, the elastic and non-elastic bouncing conditions showed visibly different profiles of position and particularly velocity. First, the racket trajectories were parsed into collision and non-collision intervals. To this end, the time of contact (t_0) and time of release of the ball (t_R) had to be identified. For both elastic and non-elastic conditions, t_0 was the time of the sample before the accelerometer signal showed the sharp change due to contact. For the non-elastic condition, t_R was the time at which the racket velocity reached a second peak and acceleration was zero after an interval of increase following the initial contact at t_0 (Figs. 3, 5). In elastic bouncing the racket velocity did not provide a systematic criterion to mark the moment of release as it decreased monotonically. Therefore, t_R was the time when the ball velocity reached its maximum following t_0 (Figs. 2, 4).³

At each time t_0 and t_R the position, velocity, and acceleration of the racket and ball were determined. Racket acceleration at t_0 was the magnitude of the accelerometer signal at the moment right before the sharp change in the accelerometer signal. (Note that for the determination of t_0 the raw signal of the accelerometer was used. For all other analyses the double-differentiated position signal was used, as the accelerometer signal showed high vibrations after the contact.) Contact duration was the difference between t_0 and t_R . Bouncing period was the time between two subsequent values of t_0 . The relative ball amplitude was determined as the difference between the position at the initial racket-ball contact and the peak height of the ball trajectory. In addition, absolute ball amplitude was defined as the peak height in the ball trajectory measured in the global coordinate frame where the floor was defined as zero.

The collisions showed a consistent profile as shown in one exemplary contact for elastic bouncing in Fig. 4 and for non-elastic bouncing in Fig. 5. Specifically the non-elastic condition allowed the interval to be further parsed into two segments. During the contact the racket velocity first decreased and then increased. The time of minimum velocity t_{Min} was determined as the landmark to partition the contact interval. t_R was defined at the second maximum which is the moment where the ball was projected into the air. Hence, a characteristic racket velocity profile during contact consisted of two segments: Segment 1 was defined between t_0 and t_{Min} and spanned the phase of negative acceleration. Segment 2 was defined between t_{Min} and t_R and spanned the phase of positive acceleration. For elastic bouncing, the ball was released from the racket without renewed racket acceleration and the contact interval could not be segmented (Fig. 4).

As further kinematic descriptors the integrals over the duration of the segments were calculated. First, velocity integrals were determined for Segment 1 and Segment 2. These measures corresponded to the distance that the racket traveled during each

³ It was not possible to apply the same criteria for determining t_R in both elastic and non-elastic conditions. For CR=0.52, the racket velocity decreased monotonically and showed no marked change to provide a good landmark to define t_R . For CR=0, the ball velocity showed a maximum shortly after the initial contact, presumably due to restitution of the ball's deformation. It was only the second peak that marked t_R . However, this second peak was more affected by the filtering and its timing was regarded as less reliable than the racket velocity's peak. Hence, our choice in the definition of t_R aimed to optimize its estimation for each of the conditions separately. As the two conditions showed different signal properties, we chose the definitions of t_R as described. Hence, no bias is expected to influence the result.

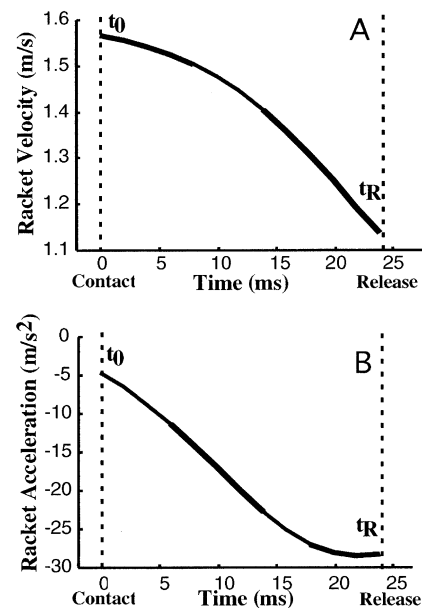


Fig. 4A, B Racket velocity and acceleration during the contact duration in the elastic bouncing condition. t_0 denotes the time of the initial contact as determined from the accelerometer signal. t_R denotes the time of ball release as determined from a second velocity peak. **A** Velocity of racket (and ball); **B** acceleration of racket (and ball)

time. Taking the integrals instead of merely the differences in position at two points in time had the advantage that non-linear changes in position were captured as well. The simple difference in position between two time points is not sensitive to the kind of linear or non-linear changes whereas the integral of velocity captures the time course (see also Fig. 9 for a larger integral). Second, integrals were computed over the racket accelerations during Segment 1 and Segment 2. These two measures corresponded to the amounts of change in velocity during each time.

In some non-elastic bouncing trials the contact intervals failed to reveal these segments. This was probably due to some mechanical noise from the apparatus and to the fact that the ball-racket system could not produce a perfect non-elastic collision (CR=0). Collisions within a trial that did not reveal the two-segmented profile were eliminated from further analysis. As long as trials contained at least 25 two-segmented collisions they were subjected to further analysis. Only two out of the total number of 90 trials had to be eliminated from the analysis.

Statistical analysis

Means and standard deviations (SD) of the kinematic measures were calculated per trial to capture mean trial performance and its variability for all conditions. Mixed-design 2x3 ANOVAs with the between-group factor CR (0 and 0.52) and the within-group factor period (714 ms, 535 ms, 417 ms) were conducted on trial means. Post hoc analyses were conducted on significant ANOVA results by using pairwise Tukey's HSD tests. The significance level was set to 0.05.

Several correlation analyses were conducted for the racket kinematic measures. First, correlations were conducted separately for each trial, where each trial had approximately 40 collisions depending on the bouncing period. To obtain average correlation coefficients across trials, the correlation coefficients were initially transformed into the Fisher z -scores according to the formula:

$$z = \frac{1}{2} \log_e \left(\frac{1+r}{1-r} \right)$$

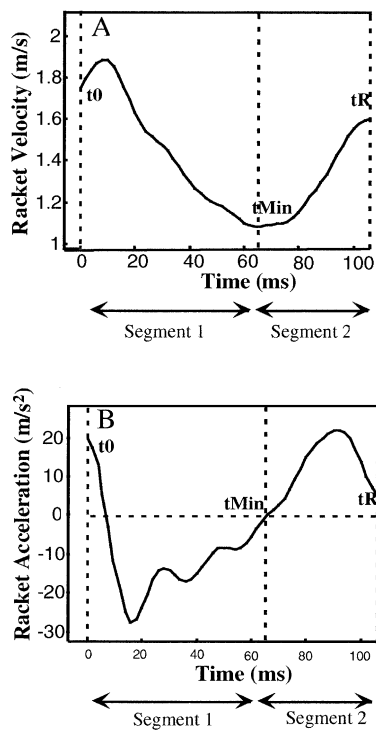


Fig. 5A, B Velocity and acceleration profile of the racket trajectory during the contact interval in the non-elastic condition. t_0 denotes the time of the initial contact as determined from the accelerometer signal. t_R denotes the time of ball release as determined from the second peak in the velocity profile. t_{Min} denotes the time of the velocity minimum, parsing the interval into two distinct segments. **A** Velocity of racket (and ball); **B** acceleration of racket (and ball)

Subsequently, group average scores were computed and subjected to analyses of variance.

Results

Description of task performance

A first evaluation of task performance established that participants actually followed the metronome period according to the instruction. Trial means of bouncing

periods were submitted to a 2 (CR) \times 3 (period) ANOVA and revealed a significant main effect for period ($F_{(2,20)} > 1000$; $P < 0.001$), but not for CR ($P = 0.255$). The overall means and their standard deviations are tabulated in Table 1. While in the slower period conditions participants performed slightly faster than prescribed, they showed slightly slower periods than prescribed for the fast metronome periods. The intermediate periods were reproduced relatively accurately, suggesting that their preferred period was close to the intermediate condition.

Concomitantly, the relative ball amplitudes were submitted to the same ANOVA. Again, the amplitudes were necessarily different for the three period conditions ($F_{(2,20)} = 888.73$; $P < 0.0001$), but no other effects yielded significance. (The relative ball amplitude was determined between racket contact and subsequent peak.) The mean values are listed in Table 1. To test the performance criterion of absolute amplitude in external space, i.e., between the ball peak and the floor, the means of the absolute ball amplitudes were also examined. Again, significant differences between the period conditions were seen ($F_{(2,20)} = 143.04$; $P < 0.001$), but not between the two CR conditions ($P = 0.149$). Note that absolute ball amplitudes were theoretically independent from the measured periods. If ball-racket contact positions varied, then these two measures could lead to different values and different variability estimates. But, again, only the instructed period differences were identified and no interactions reached significance. These results confirmed that participants performed the task relatively close to the periods and amplitudes prescribed. Importantly, the two CR conditions had no effect on this primary performance criterion.

A second performance test examined the variability in the kinematic cycle measures. Standard deviations of bouncing period were submitted to the same 2 \times 3 ANOVA. No significant main effects were revealed. However, the interaction between CR and period was significant, showing that the variability for CR=0 decreased monotonically from the longest to the shortest period, $F_{(4,40)} = 2.64$; $P < 0.05$. In contrast, for CR=0.52, the standard deviations showed a minimum for the intermediate period and were elevated for the short and the long periods (see Table 1). This indicated that for the elastic

Table 1 Periods (ms) and the relative ball amplitudes (m) within each period and bouncing condition. The means and standard deviations were calculated over all participants and trials

	Bouncing condition	Period condition	Mean \pm SD
Period	CR=0	714	662 \pm 43
		535	534 \pm 40
		417	427 \pm 27
	CR=0.52	714	696 \pm 35
		535	532 \pm 28
		417	418 \pm 43
Relative ball amplitude	CR=0	714	0.31 \pm 0.06
		535	0.18 \pm 0.04
		417	0.10 \pm 0.03
	CR=0.52	714	0.34 \pm 0.04
		535	0.19 \pm 0.03
		417	0.11 \pm 0.03

condition a preferred regime existed, while for the throwing-like movements in CR=0 the variability scaled with period. This interpretation was confirmed when the coefficients of variation were calculated. The values were constant for CR=0 and showed a U-shaped pattern for CR=0.52. Analyzing the variability in the absolute and relative amplitudes in the same fashion, the results only showed a main effect for period, such that more variability was observed for longer bouncing periods ($F_{(2,20)}=35.44$; $P<0.0001$) and ($F_{(2,20)}=25.41$; $P<0.0001$) respectively (see also Table 1).

In summary, the comparison between kinematic descriptors of elastic and non-elastic bouncing showed no difference in mean performance. In contrast, variability in task performance differed such that in the elastic condition a preference for the intermediate periods was observed. In the non-elastic condition variability increased with amplitude and period.

Elasticity of the contact

Given the similarity of the mean performance, a further test aimed to verify that there was indeed a difference in the elastic nature of the contact. In contrast to the experimental determination of the coefficient of restitution where the racket was held stationary, the racket was moving in the experimental trials and more “control” could also be part of the elastic bouncing condition. To examine the degree of elasticity in the two CR conditions, the relative velocities of ball and racket before and after contact were examined. According to the definition of elastic impact and the coefficient of restitution, incoming and outgoing velocities should be linearly related.

For all ball-racket contacts in all trials per participant the relative velocities between ball and racket at release were regressed against the relative velocities of ball and racket at the initial contact (Fig. 6). For CR=0.52 significant regressions were obtained as expected, with the negative slopes ranging between 0.50 and 0.56 (r^2 's ranged between 0.66 and 0.83). The slopes were negative because the ball velocities during the falls and rebounds were in opposite directions. Panel A of Fig. 6 shows the velocity pairings of each impact of one representative participant in the elastic condition (slope=0.53, $r^2=0.71$). On panel B the mean values of all trials are displayed. The means scale with the period condition such that slower periods are associated with a higher velocity at contact and release to project the ball to a higher amplitude. The slopes approached the experimentally determined coefficient closely and the r^2 values ranged between 0.92 and 0.99 for the individual participants. Panels C and D show the same regressions performed on data of another participant in the non-elastic condition. The data cloud of the individual contacts is less clustered around the regression line (r^2 values of the six participants were only around 0.20 with one higher value of 0.42). The regression on the means had a slope of 0.21 with an r^2 of 0.27.

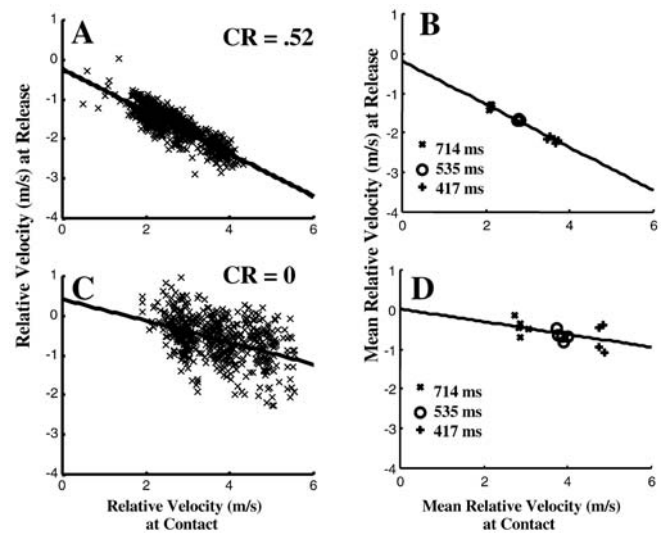


Fig. 6A–D Relative velocities between ball and racket at initial contact plotted against the relative velocities at release. **A** and **B** show this relation for the elastic condition. In **A** the data of all contacts of all trials of one participant are plotted. In **B** the trial means of the same participant are shown. **C** and **D** show the non-elastic condition. Individual contact data are displayed in **C** and trial means for the same participant are shown in **D**

These results revealed that in CR=0.52 the elastic nature of the contact was predominant and only marginally influenced by the performer during the contact interval. Conversely, at CR=0 the relative velocities did not relate systematically between the initial contact and release, suggesting that the performer modified the ball-racket kinematics actively during the contact.

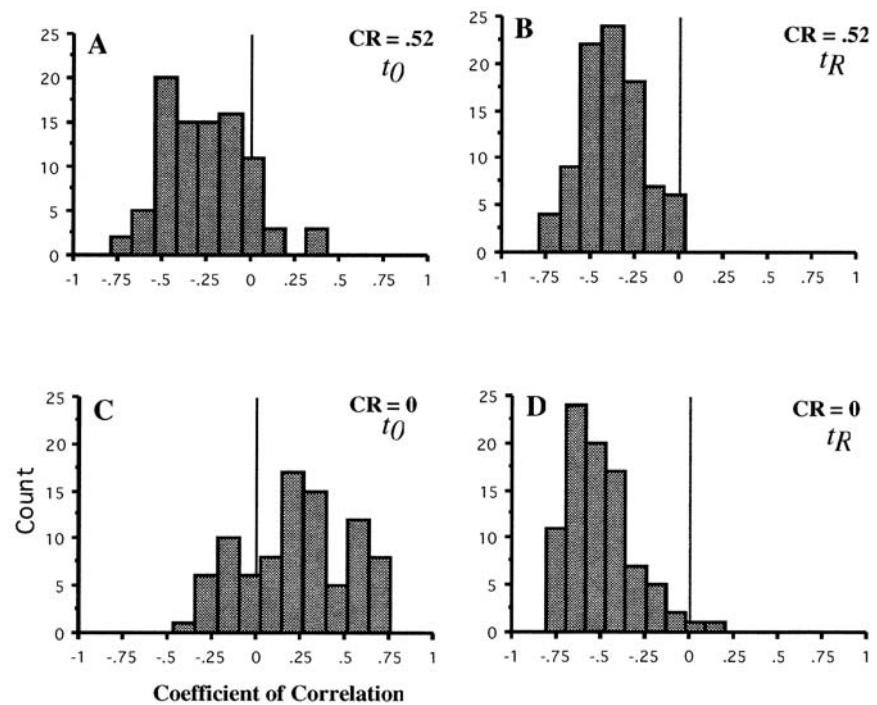
Racket acceleration at contact

The different elasticity conditions evidently required different ball control strategies. The first candidate variable for documenting such differences was racket acceleration at contact. In previous studies on elastic ball bouncing the acceleration of the racket was identified as the essential variable that characterized stable bouncing performance. Negative acceleration just prior to contact signified dynamically stable bouncing for elastic conditions. Trial means of racket accelerations in the different conditions were compared with the same 2×3 ANOVA. The difference between the CR conditions was highly significant, $F_{(1,10)}=81.64$; $P<0.0001$: The overall mean value for the elastic conditions was negative, 0.415 ± 0.31 m/s², while it was positive for the non-elastic conditions: $+0.408\pm 0.18$ m/s². The interaction and the main effect for frequency were not significant.

Contact duration

A second candidate for capturing the differences in the two CR conditions was contact duration. In non-elastic

Fig. 8A–D Histograms of correlation coefficients between racket position at initial contact t_0 and at release t_R . **A** and **B** show the two distributions for the elastic condition. **C** and **D** show the distributions for the non-elastic bouncing condition



Correlations between racket position and velocity

In order to obtain a specific ball amplitude in external coordinates, the law of ballistic flight requires that the release velocity should be inversely proportional to the position at which the ball is hit. Thus, for a given target height, a lower contact position requires a higher ball release velocity and vice versa. Following on from the preceding results, showing that for both CR conditions similar absolute mean amplitudes were obtained, we expected significant negative correlations between the racket position and velocity at t_R . Conversely, if some control was exerted during the contact interval, the position and velocity did not need to be as tightly correlated at t_0 . To examine these relations, for each trial the racket positions in external coordinates and racket velocities at the initial contact t_0 and at the moment of release t_R were correlated. The correlation coefficients of all trials and participants for one CR condition were pooled into a histogram and are displayed in Fig. 8.⁴ For CR=0.52, panels A and B display the distribution of the coefficients of correlation at t_0 and t_R , respectively. Although the distribution tends to form a slightly tighter peak at t_R , there is relatively little change in the average value from t_0 to t_R . Both show significant negative correlations. In contrast, for CR=0, shown in panels C and

D, there is a visibly flatter distribution for the correlation coefficients at t_0 around zero, while at t_R a clear mode around -0.70 is established. To evaluate whether differences occurred as a function of period, all correlation coefficients were transformed into z -scores and a 2 (CR) \times 2 (t_0 and t_R) \times 3 (period) ANOVA was conducted. Correlations were different for the two CR conditions, consistent with the illustrative histograms, $F_{(1,8)}=16.13$; $P<0.01$. They were also significantly different for t_0 and t_R , $F_{(1,8)}=46.33$; $P<0.001$. A significant interaction between CR and t_0 and t_R verified the qualitative description of the distribution data, $F_{(1,8)}=23.73$; $P<0.01$. Different period conditions, however, did not produce any differences in the result.

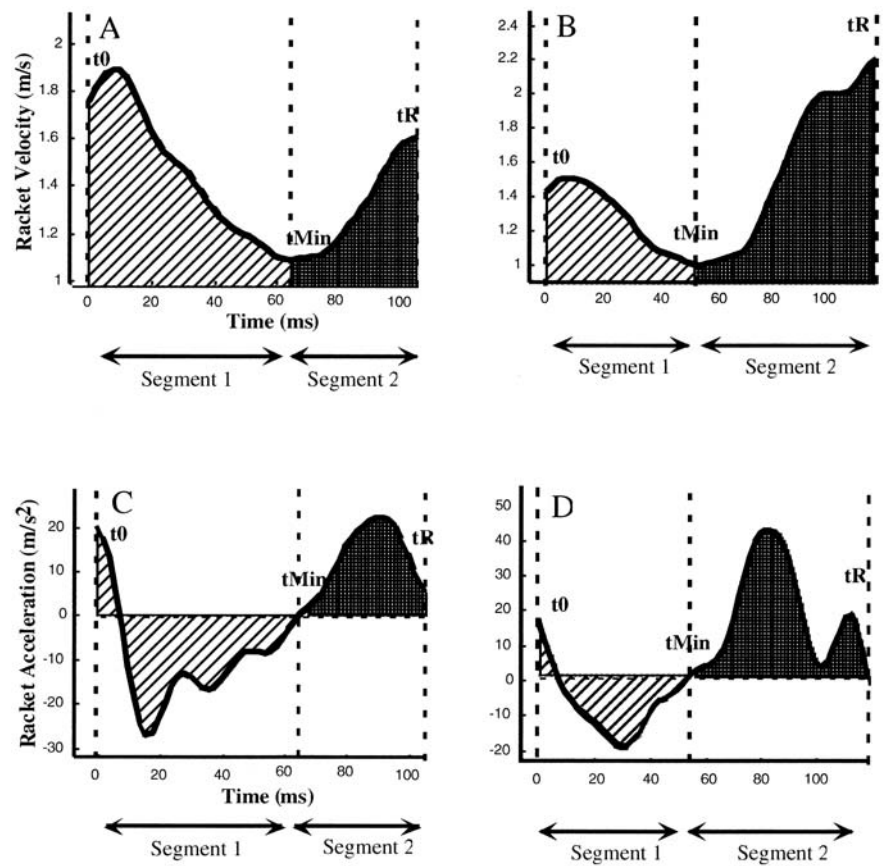
In sum, correlations between position and velocity reveal that in CR=0 there was a significant modification of the racket position and velocity relationships during the contact interval towards the required negative correlations at release. This was not the case for CR=0.52, leading to the conclusion that all control for the correct position-velocity relations had been established prior to contact.

Correlation between segments

To further elucidate to what degree control could be identified in the non-elastic condition during the contact interval itself, the interval was decomposed into two segments. Segment 1 was the phase of deceleration after contact and Segment 2 comprised the positive acceleration phase which led to the projection of the ball (Figs. 3, 4). Correlation analyses compared the velocity and acceleration integrals for the two segments of the contact

⁴ z -scores of correlation coefficients were introduced for the analyses of variance, as the analysis requires normal distributions of its variables and correlation coefficients do not guarantee this. However, for the visualization of the correlation coefficients obtained in the trials, we regarded the untransformed values as more intuitive. Hence, we kept the Pearson's correlation coefficients for the histograms.

Fig. 9A–D Two exemplary trajectories of collision intervals in the non-elastic bouncing condition. **A** and **B** show two velocity profiles where the *hatched areas* illustrate that a smaller integral in Segment 1 is followed by a larger integral in Segment 2 and vice versa. **C** and **D** show two acceleration profiles with the same complementary relation between the areas under Segments 1 and 2



interval to identify systematic control across these two phases of ball contact. The correlations were performed for each trial separately between the velocity integrals of Segments 1 and 2. The z -scores of these correlation coefficients were averaged across all period conditions. The average z -score for the correlations between the velocity integrals of Segments 1 and 2 was 0.80, signifying that larger racket displacements in Segment 1 were followed by smaller displacements in Segment 2, and vice versa. Two such exemplary contact intervals are displayed in Fig. 9A, B. On panel A the large integral in Segment 1 is followed by a smaller integral in Segment 2. The converse relations are shown in panel B. Similarly, significant negative correlations were observed for the acceleration integrals in Segments 1 and 2, expressing that higher velocity changes in the first segment were followed by smaller changes in the second segment. Two such contact intervals are shown in panels C and D of Fig. 9. The mean z -score of all trials was 0.62. Additionally, the correlations between the velocity integral of Segment 1 and the acceleration integral of Segment 2 yielded a mean correlation coefficient of 0.81. Between the acceleration integral of Segment 1 and the velocity integral of Segment 2 the average z -score of the correlation coefficients was 0.90. These negative correlations confirmed that highly systematic relations existed between the two segments of contact suggesting some

form of control during the contact interval in the non-elastic collisions.

Discussion

Hitting or throwing a ball or an object accurately to a target location is found in many everyday and sports activities. A series of previous studies investigated the rhythmic hitting of a ball with an invariant amplitude and revealed that control of the ball trajectories can be obtained by establishing a regime that has dynamical stability (Schaal et al. 1996; Sternad et al. 2000, 2001). To achieve dynamical stability in a motor task has the advantage that perturbations need not be corrected for by “expensive” feedback-based corrections. That this parsimonious strategy is indeed a viable candidate for control was demonstrated by comparing human performance parameters with model predictions that were derived from stability analyses. For the rhythmic bouncing of a ball, the authors showed that actors indeed exploit this regime. However, the model rested on a few assumptions, including an instantaneous impact. This, of course, never happens in the real physical events. A subsequent study highlighted this fact by showing that perceptual information, particularly about the contact, provided salient information for obtaining a dynamically stable performance. This suggests that information and control of the

contact may play a role in the rhythmic control of a ball – over and above dynamical stability.

To test how control is exerted when the contact interval is not instantaneous, two different ball-racket conditions were contrasted. An elastic condition with a relatively short contact interval was assessed, where dynamical stability was expected to play the dominant role, consistent with previous results. The ball-racket contacts are primarily prepared in advance. In a non-elastic condition the contact energy has to be injected into the ball and control of the contact event becomes necessary. The hypothesis is that control will be exerted during the contact interval.

First descriptive analyses of the non-elastic and elastic performance showed that the tasks were achieved with similar success. The average ball amplitudes and periods per trial did not differ. It was only the estimates of period variability that indicated that in the elastic condition there was a preference for the intermediate periods. For throwing-like movements the variability showed the expected decrease with lower amplitudes, consistent with Weber's law or multiplicative noise. Regressions of relative velocity at the initial contact and at release revealed that in condition CR=0.52 the coefficient of restitution was close to the one determined under stationary conditions. It suggested that the racket movement did not add extra energy into the ball at release. In contrast, for condition CR=0 there was no consistent coefficient of restitution, indicative that active throwing actions took place. Testing the hypothesis of dynamical stability, racket accelerations were calculated. Consistent with the hypothesis, racket accelerations before contact differed systematically between the two CR conditions. For CR=0.52 the acceleration was robustly around -4 m/s^2 , as demonstrated several times previously, supporting that participants utilized the strategy that attuned to the dynamical stability of the task (Sternad et al. 2000, 2001). For CR=0, on the other hand, the value was positive with a mean of $+4 \text{ m/s}^2$, indicating a dynamically unstable regime. To achieve consistent ball amplitudes, a control mechanism acting during the collision phase is expected to play a role.

Corroborating the picture that control must have been applied during the contact periods in the non-elastic bouncing condition were the results on the correlations between position and velocity at initial contact and release. While a negative correlation at the release was mechanically required to obtain a relatively invariant ball amplitude, it was interesting that in the elastic bouncing condition this correlation already existed at initial contact and remained negative at the moment of release. For non-elastic bouncing, on the other hand, this necessary negative correlation was only established throughout the contact interval, as histograms and statistical analyses clearly demonstrated. It was only at release that higher contact positions in space were systematically accompanied by lower racket velocities, and vice versa.

The extent of such control of the racket movements was further assessed by an analysis of the continuous

kinematics during the contact interval. According to the mechanics of impacts, the velocity of the racket for CR=0.52 decreased immediately after initial contact and continued to decrease monotonically throughout the entire contact interval. This was accompanied by an abrupt change in ball velocity from negative to positive, changing the direction of flight due to the collision. For CR=0, a consistent pattern with two peaks in the velocity profile was observed, paralleled by a phase of negative and positive acceleration, respectively. Following the initial contact, the racket velocity decreased monotonically in what we defined as Segment 1. This decrease in racket velocity was induced by the reactive impulse, which acted against the impulse that compressed the ball and changed the direction of the ball movement (Shames 1997; Stronge 2000). This segment of the velocity profile corresponded to the first part of the elastic impact, the period of deformation. However, in the perfectly non-elastic collision restitution of elastic energy does not occur, the potential energy of deformation energy is completely dissipated, and ball and racket move with a common velocity. To project the ball, the racket needed to accelerate the ball. This active component defined Segment 2, where the ball was accelerated and energy was imparted to the ball due to muscle work.

To satisfy the mechanical requirement for invariant bouncing amplitudes, i.e., negative correlation between the release position and release velocity, the racket movement is expected to be controlled to attain this position-velocity relationship. Hence, it was expected that, if the distance traveled by the racket movement during Segment 1 is larger, the displacement during Segment 2 should be smaller. Equivalently, larger displacements during Segment 1 should be followed by a smaller amount of velocity change (i.e., smaller increase in the velocity) in Segment 2. The correlation analyses of the velocity integral as well as of the acceleration integral indeed revealed such negative correlations. Given that there was no correlation between position and velocity at the initial contact, it must have been this compensatory relationship that obtained the required negative position-velocity relationship at the release.

Two things are important to note here: First, these compensatory relationships between the two segments occurred on a remarkably short time scale; second, it is the haptic modality that is the predominant source of sensory information. The average contact duration for CR=0 was 116 ms, with trial averages ranging between 86 and 136 ms. Compensatory regulation happened within the latter part of this interval, that is on average within 58 ms. Physiologically, this time window does not allow for feedback-based cortical control loops. Hence, spinal or supraspinal loops must have regulatory functions. Still, the times are remarkably brief. One account for the speed of regulatory control may be that it is haptic or kinetic information that guides this fine control. Typically, when sensory control has been examined, visual information is present. From reaction time studies it is known that kinesthetic stimuli have shorter reaction times than visual

stimuli; hence regulatory loops initiated by haptic information may be shorter than visually based regulation.

In the literature some studies have reported adjusted muscle activity in hand-object interactions on similarly short time scales. For instance, when subjects hold and lift an object with an opposition grip, fine modulation of grip force has been observed. As movements of hand-held objects in the gravitational field constantly require the adjustment of grip force to prevent the object from slipping, Flanagan and colleagues showed how grip force was finely modulated in phase with load force (Flanagan et al. 1993; Flanagan and Wing 1995). However, in these studies the actors were in control of their actions and could visually monitor their hand and thereby probably coupled force control and displacement in an anticipatory fashion. In another line of experiments, Johannson and Westling (1988) applied perturbations to the load, either by the subject him/herself or by the experimenter, that were unanticipated by the subject. In self-induced perturbations, the authors reported a triggered response such that muscle activity increased rapidly after perturbation onset at a latency of 35–65 ms, where the variability was due to the different involved muscles. The grip force changed with a small delay at approximately 80 ms after perturbation onset. Such triggered response was functional in that it contributed to quickly restoring the grip force necessary to prevent slipping. The authors conjectured an M2 or preprogrammed response, which is commonly considered to be supraspinally mediated. It has been conjectured that the cerebellum is involved for centrally setting the preparatory grip force level and the gain of triggered reflex (Winstein et al. 2000).

If the perturbation was anticipated, additional preparatory muscle activity 150 ms prior to the onset of the perturbation was observed. Both preparatory and triggered activity lead to contraction in both agonistic and antagonistic muscle, i.e., coactivations. This shows that these responses are not mere stretch reflexes, as otherwise only reciprocal activation would have been observed. In unpredictable perturbations Johannson and colleagues found that the triggered response in grip force occurred after 80 ms and was scaled with the rate of change of the load force (Johannson et al. 1992a, 1992b). In our results on the haptic modulation of ball release it is probably this M2 response that underlies the functionally adjusted complementary relationship between parameters in Segments 1 and 2.

Rapid and adapted muscle activation was also observed in ball catching by Lacquaniti and Maioli (1987, 1989). Participants were asked to catch a ball that was dropped vertically onto the hand with the elbow joint held at right angles. Preparatory muscle coactivation was observed approximately 125 ms prior to the ball contact with the hand. Importantly, this EMG activity was scaled with respect to the ball momentum at ball-hand contact and counteracted the ball momentum and stabilized the arm configuration. More importantly with respect to the ball bouncing results is that after the initial contact, the

EMG showed a rapid increase with a very short latency of 14–22 ms, again involving coactivation of agonist and antagonist rather than reciprocal stretch reflex as to be expected from the monosynaptic stretch reflex. Despite its brevity, this modulation of reflex mechanisms must be preset supraspinally.

Lastly, in a study on the table tennis forehand drive, Bootsma and van Wieringen (1990) showed compensatory variability in kinematic and perceptual variables. Expert players who executed a forehand drive with a movement time between 92 and 158 ms showed functional variations in the bat's trajectory within this time window. For instance, if the initiation of the drive is late, the racket was more accelerated to propel the ball to the specified target location. Similarly, the angle of the bat was adjusted such that the variability of the bat's direction of travel decreased right until the contact with the ball. The authors conclude that even in such rapid expert performances there are no memorized action programs but a continuous action-perception coupling that apparently operates on a very short time scale. These and the preceding experimental results illustrate that haptically modulated object manipulation can be controlled within extremely short time scales. This is probably achieved by some distributed subcortical control loops that exploit and modify spinal reflex loops.

To conclude, the results of the present study confirm that performers use qualitatively different strategies for the propulsion of a ball depending on the elasticity of the ball-racket collision. Consistent with predictions for dynamical stability derived previously, elastic contacts are controlled prior to contact and exploit properties of dynamical stability by contacting the ball with a decelerating racket movement. The more energy that is lost during the contact, the more control has to occur during the collision interval. Such fine control of the relevant variables during contact is obtained by information-based compensatory adjustments within the extremely short time window.

Acknowledgements This research was supported by the National Science Foundation, grant no. SBR 97-1031297 and Behavioral Neuroscience grant no. 00-96543. We would also like to thank the Kligman Foundation for its support of Hiromu Katsumata.

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