

Deliberate utilization of interaction torques brakes elbow extension in a fast throwing motion

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Abstract We tested the hypothesis that in fast arm movements the CNS deliberately utilizes interaction torques to decelerate (brake) joint rotations. Twelve subjects performed fast 2-D overarm throws in which large elbow extension velocities occurred. Joint motions were computed from recordings made with search coils; joint torques were calculated using inverse dynamics. After ball release, a large follow-through shoulder extension acceleration occurred that was initiated by shoulder extensor muscle torque. This shoulder acceleration produced a flexor interaction torque at the elbow that initiated elbow deceleration (braking). An instantaneous mechanical interaction of passive torques then occurred between elbow and shoulder, i.e., elbow extension deceleration produced a large shoulder extensor interaction torque that contributed to the shoulder extension acceleration which, simultaneously, produced a large elbow flexor interaction torque that contributed to elbow extension deceleration, and so on. Late elbow flexor muscle torque also contributed to elbow deceleration. The interaction of passive torques between shoulder and elbow was braked by shoulder flexor muscle torque. In this mechanism, shoulder musculature contributed to braking elbow extension in two ways: shoulder extensors initiated the mechanical interaction of passive torques between shoulder and elbow and shoulder flexors dissipated kinetic energy from elbow braking. It is concluded that, in fast 2-D throws, the CNS delib-

erately utilizes powerful interaction torques between shoulder and elbow to brake motion at the elbow.

Keywords Interaction torque · Overarm throwing · Human · Mechanical interaction · Leading joint hypothesis

Introduction

For multijoint arm movements, there is increasing evidence that passive interaction torques, which occur at one joint due to motion at adjacent joints, are controlled by the CNS in different ways according to the task. In some situations where accuracy was required, interaction torques were compensated for, i.e., muscle activity opposed interaction torques (e.g., Gribble and Ostry 1999; Hollerbach and Flash 1982; Koshland et al. 2000; Pigeon et al. 2003). Alternatively, in a variety of tasks of moderate to fast speed, interaction torques may be purposely generated to exploit the property that proximal segments of human limbs have higher inertia and larger musculature than distal segments (Dounskaia 2005). For example, a number of arm movement tasks have been reported in which interaction torques were exploited depending on the movement context (e.g., Schneider et al. 1989; Dounskaia et al. 1998, 2000, 2002; Galloway and Koshland 2002; Buchanan 2004; Lee et al. 2007; de Rugy et al. 2006; Furuya and Kinoshita 2008). Similarly, in fast throwing, interaction torques may be exploited by skilled subjects to increase distal joint angular velocities (Feltner 1989; Hong et al. 2001; Hirashima et al. 2003, 2007; Debicki et al. 2004; Gray et al. 2006).

In addition to a role in accelerating joint motions, interaction torques could be utilized to decelerate (brake) joint motions. For example, in fast kicking, forward motion of the thigh was decelerated (braked), not by antagonist

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muscle activity, but by an interaction torque resulting from motion of the lower leg (Putnam 1993; Sorensen et al. 1996). Similarly, in 2-D throwing, shoulder deceleration before ball release resulted from an interaction torque from elbow motion and not from shoulder antagonist muscle activity (Hirashima et al. 2003; Debicki et al. 2010). However, in these two cases, it is not clear whether slowing at the proximal joint was a purposeful strategy or was simply a fortuitous coincidence.

The objective of the present study was to systematically investigate the role of interaction torques in a situation in which rapid braking was the desired outcome. Such is the case at the elbow in fast 2-D throwing where it is necessary to produce rapid elbow deceleration after ball release to avoid injury. Furthermore, 2-D throwing is a natural (dart-like) movement for which torques are relatively easy to calculate. The hypothesis was that in fast arm movements, the CNS deliberately utilizes interaction torques to decelerate (brake) joint rotations. The results show that for fast 2-D throws, the CNS initiates a follow-through motion at the shoulder that generates an interaction torque at the elbow which, by means of a mechanical interaction effect of passive torques between shoulder and elbow, contributes to the rapid braking of elbow extension.

Methods

Subjects and procedures

The study was approved by the University of Western Ontario Ethics Review Board, and all subjects gave informed consent. A total of 12 male subjects participated whose age was 21–24 years. All were right-handed skilled

recreational throwers. Subjects made 2-D overarm throws from a sitting position with the chest constrained from moving forward by means of straps pulled tightly over the shoulders. The participants were instructed to throw accurately using a baseball (150 gm). Sets of 20 2-D throws were made in the following order: slow, medium, fast, and medium. Only the fast throws were analyzed in detail. For the fast throws, subjects were instructed to throw as fast as possible and accurately, and they were free if they wished to increase the amplitude of shoulder motion by increasing the backswing (shoulder flexion). Subjects were allowed to practice throws until they were comfortable at all speeds.

Subjects were instructed to keep the arm in a parasagittal (vertical) plane (Fig. 1). Throws were excluded if they came out of the plane as observed either by an experimenter standing behind the subject or by off-line analysis of each throw. Throws were also excluded if their speed or accuracy for a particular condition was markedly different from the mean for that subject, i.e., were outside the range of 95% of throws which is given by $SD \times 3.92$. On average, 16 fast throws/subject were analyzed. Throws were made on command about every 30 s at a vertical grid of 6×6 cm numbered squares (9 squares across and 27 high). The target was a square of 6×6 cm at about eye level and 3.1 m from the chest. Each throw was scored for accuracy by the participant calling out the number on the square that was struck.

The timing of ball release from the tip of the middle phalanx was measured with a pressure-sensitive micro-switch (trigger) that was attached to the distal phalange of the middle finger. The participants were instructed to grip the ball with the middle finger so that the ball rolled over the distal switch. The timing accuracy of the distal microswitch was verified by comparing it with the time of onset of finger

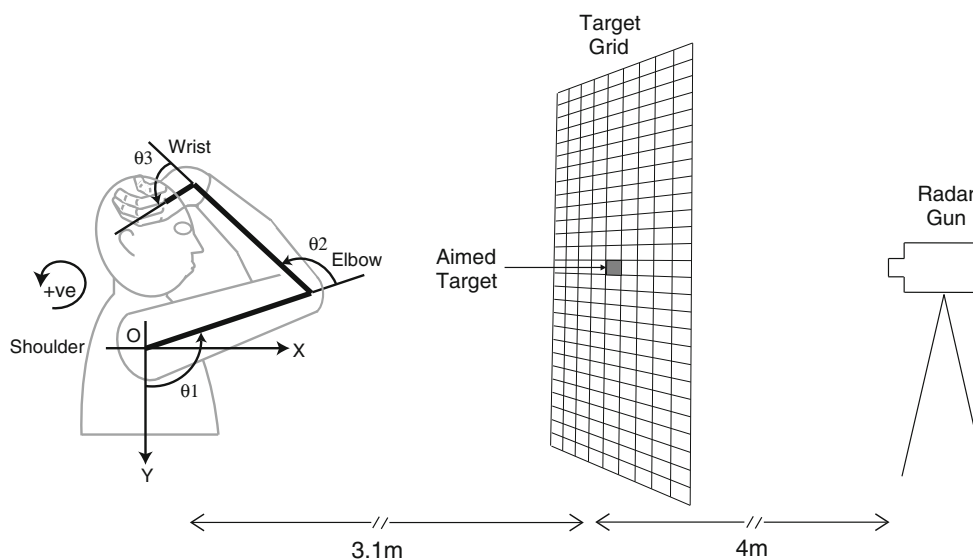


Fig. 1 Diagram of the experimental setup and joint angles in the 2-D 3-joint throwing task

flexion after finger extension, which is a moment in fast throws that coincides with release of the ball from the fingertip (e.g., Hore et al. 1999). Ball speed was measured with a radar gun (Stalker Professional Sports Radar, sampling rate 100 Hz) that was located about 4 m behind the target curtain (i.e., about 7 m from the participants).

Recording angular positions of arm segments

Angular positions of five arm segments and the trunk were measured using the magnetic-field search-coil technique as described previously (Tweed et al. 1990; Hore et al. 1996). Search coils were securely taped to the back of the distal phalanx, the back of the hand, the back of the forearm proximal to the wrist, the lateral aspect of the upper arm, the acromion process of the scapula, and the sternum. The participants sat in 3 orthogonal alternating magnetic fields of frequency 62.5, 100, and 125 kHz generated by $3 \times 3 \times 4$ m Helmholtz coils. Coil voltages, sampled at 1,000 Hz, were used to calculate the simultaneous angular positions of each arm segment and the trunk in three-dimensional space. Arm motions were described in terms of joint rotations by computing angular positions of arm segments with respect to the adjacent proximal segment. In this case, the axes were embedded in the proximal segment and rotated with it. Shoulder joint angle was defined relative to the vertical axis passing through the shoulder joint, elbow joint angle was defined relative to the long axis of the upper arm, and wrist joint angle was defined relative to the long axis of the forearm (Fig. 1). Positive joint angles were in the counter-clockwise (upwards) direction (shoulder flexion, elbow flexion, and wrist extension). Joint angular velocities and accelerations were obtained by differentiation. Shoulder, elbow, and wrist joint kinematics were low-pass filtered using Matlab (The Mathworks) with a second-order Butterworth filter at 20, 30, and 45 Hz, respectively, because of the different frequencies of joint kinematics. At the start of each experiment, a calibration was performed in which the upper arm was horizontal and pointing forward, and the forearm pronated such that the forearm, hand, and fingers were in a vertical line with the palm facing forward. This position (0) was used as the reference position in the kinematics figure (Fig. 2).

Joint dynamics

Shoulder, elbow, and wrist torques were computed using inverse-dynamics equations of motion for a 2-D (vertical plane) 3-joint planar link-segment model of the human arm as described by Hirashima et al. (2003). The arm model included translations of the origin in a parasagittal plane in vertical (Y) and horizontal (X) directions. Translational movements of the origin were recorded using Optotrak at 500 Hz.

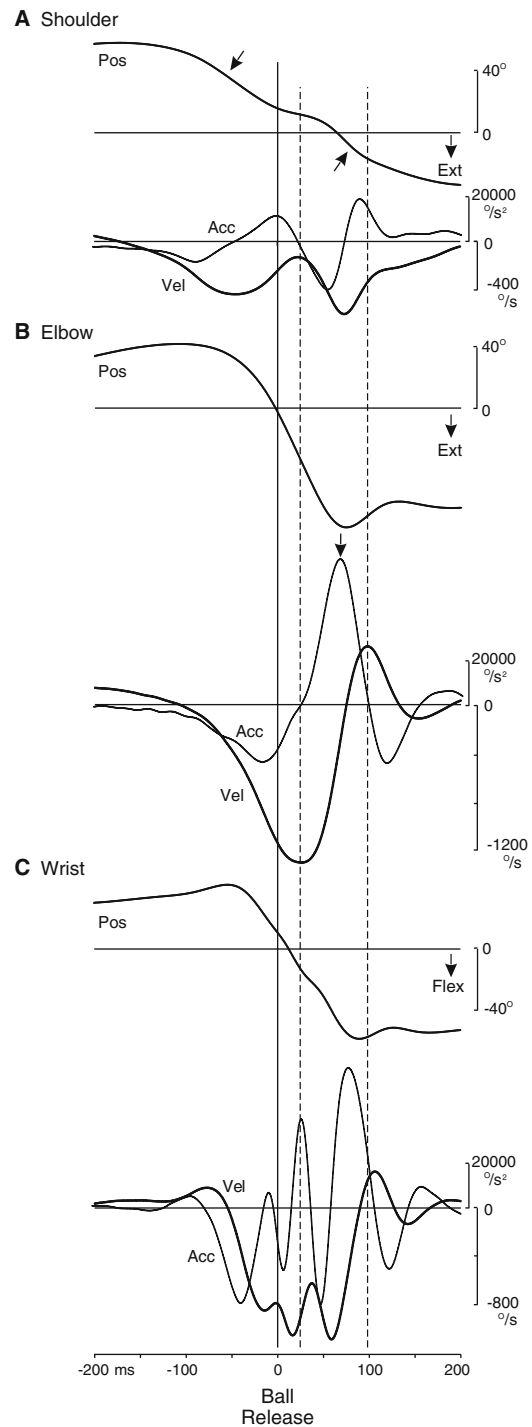


Fig. 2 Average angular positions, angular velocities, and angular accelerations of joint rotations at shoulder, elbow, and wrist from a representative subject. Each trace is the average of 16 throws aligned on the time of ball release (solid vertical line). Dashed lines indicate period of elbow extension deceleration. Diagonal arrows indicate the two periods of shoulder extension: initial motion before ball release and follow-through motion after ball release

Translations were linearly interpolated and resampled at 1,000 Hz off-line and were temporally aligned with the angular search coil data using an analog step signal that was sampled

from a channel common to both motion acquisition systems. Translation positions were subsequently low-pass filtered at 15 Hz and differentiated to obtain linear velocities and accelerations of the origin. Anthropometric variables were computed for each individual subject based on constants defined by Winter (2005). The mass of the ball was incorporated into the model until ball release when it was set to zero. This resulted in an instantaneous step in the torque records at the time of ball release. The equations of motion were used to compute the net torque (NET), the muscle torque (MUS), the interaction torque (INT), and the torque due to gravity (GRA) for each of the shoulder, elbow, and wrist joint. Torque variables were defined according to previous studies (e.g., Hollerbach and Flash 1982; Bastian et al. 1996, 2000; Gribble and Ostry 1999; Cooper et al. 2000; Hirashima et al. 2003; Debicki and Gribble 2004; Debicki et al. 2010) where the NET torque was proportional to angular acceleration and was defined as the sum of the other components ($\text{NET} = \text{MUS} + \text{INT} + \text{GRA}$) and where the MUS torque parameter is computed as a residual value ($\text{MUS} = \text{NET} - \text{INT} - \text{GRA}$). Thus, the MUS torque is a generalized muscle torque that includes both torque generated from muscle activation and torque generated from the passive properties of the muscle and other joint tissues.

To quantify the computed joint dynamics, interaction torques were integrated over various time windows for each individual throw to compute a torque impulse that was then averaged for each subject and averaged across subjects. The elbow interaction torque consisted of 8 motion-dependent components; the shoulder interaction torque consisted of 9 motion-dependent components. These components are given in the legends for Figs. 4 and 5, respectively.

Statistics

Unless indicated otherwise, comparison of means was performed with a two-tailed unpaired *t* test (unpaired because the motions that were compared were different, e.g., those before and after ball release).

Results

Kinematics

Twelve subjects threw baseballs at a fast speed in a parasagittal plane. The mean ball speed was 44.6 km/h (SD 4.0). The present analysis is focused on the braking of elbow extension that occurred after ball release.

Average angular kinematics for joint rotations at shoulder, elbow, and wrist are shown for a representative subject in Fig. 2. There were two major points of interest. First, there were two separate shoulder extension motions (Fig. 2a): one before ball release (downward diagonal arrow) and a follow-

through motion after ball release (upward diagonal arrow). This shoulder extension follow-through motion occurred in all subjects. Figure 3a shows that across subjects the mean amplitude of these shoulder motions was 35° (SD 12) before ball release and 44° (SD 21) after ball release. Interestingly, across subjects (Fig. 3b), the mean shoulder extension velocity of the follow-through motion after ball release (550°/s SD 165), when the subject was slowing down his arm, was larger than that before ball release (368°/s SD 122) [$t(22) = 3.076$, $P = 0.0055$] when the subject was trying to generate fast arm speeds. Similarly, peak shoulder extension acceleration after ball release (Fig. 3c) (mean 2.75×10^4 °/s² SD 1.39) was 3.2 times larger than that before ball release (mean 0.85×10^4 °/s² SD 0.37) [$t(22) = 4.571$, $P = 0.0001$].

The second point of interest was that this follow-through motion at the shoulder after ball release occurred in association with a large elbow extension deceleration (Fig. 2b, downward vertical arrow on acceleration trace, dashed lines give onset, and offset of elbow extension deceleration). Across subjects, the mean magnitude of peak elbow extension deceleration after ball release (Fig. 3c) (6.7×10^4 °/s² SD 2.1) was 2.5 times larger than the mean magnitude of peak elbow extension acceleration before ball release (2.7×10^4 °/s² SD 0.7) ($P < 0.001$). Considering the ± 200 ms period before and after ball release, the amplitude of joint rotations across subjects (Fig. 3a) was elbow 111° (SD 16) and wrist 112° (SD 17). Across subjects (Fig. 3b), peak elbow extension velocity was 1,228°/s (SD 157) and maximal wrist flexion velocity was 1,520°/s (SD 490).

In summary, the kinematics showed that there was a large follow-through extension acceleration at the shoulder after ball release that occurred at the same time as a large elbow extension deceleration. To determine the relation between these motions, we performed a dynamics analysis.

Elbow dynamics

A prediction from the hypothesis is that an interaction torque will occur at the elbow, which contributes to the deceleration of elbow extension. To test this prediction, elbow dynamics were computed using inverse dynamics. The computed elbow torques for the representative subject are shown in Fig. 4a–d as a function of time. The dashed lines give the onset and offset of elbow flexor net torque (which occurs simultaneously with elbow deceleration). Each trace represents the average of 16 throws aligned on ball release (solid vertical line). Figure 4a shows that from the start of the throw there was a period of elbow net torque in the extension direction until about 25 ms after ball release, which was followed by a large elbow net torque in the flexion direction. This elbow flexor net torque (Fig. 4a) arose from a combination of elbow flexor interaction torque (Fig. 4c) and elbow flexor muscle torque (Fig. 4b). Onset of the elbow flexor net torque (Fig. 4a, left dashed line)

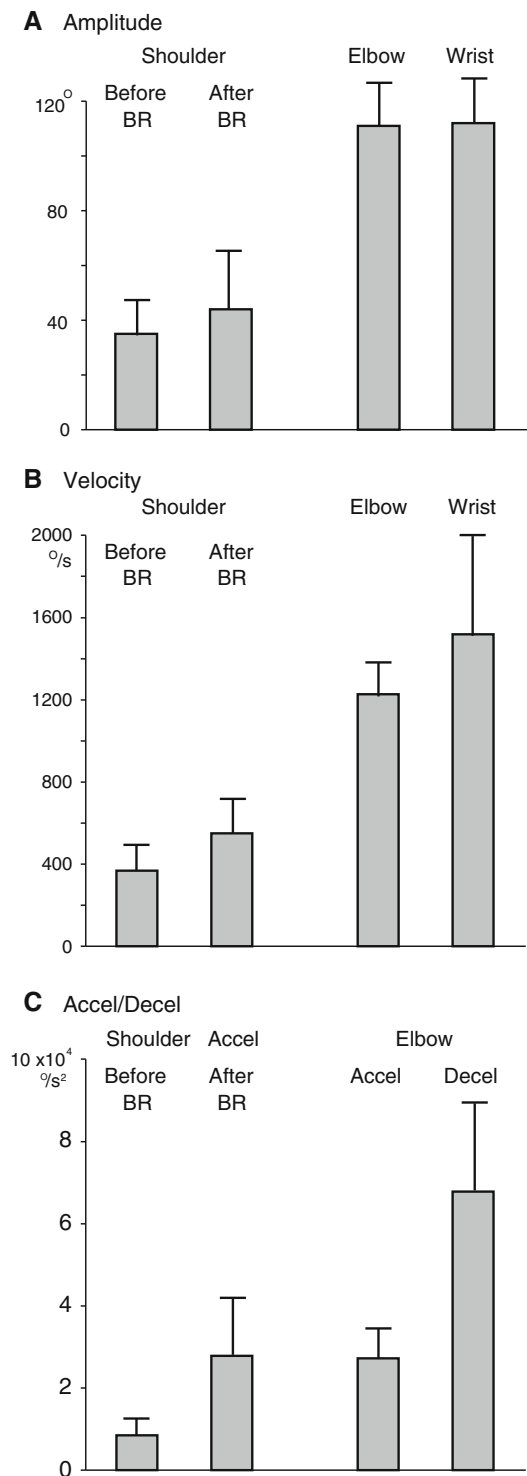


Fig. 3 a, b Means and SDs of joint angular amplitudes and joint angular velocities across subjects from 200 ms before to 200 ms after ball release (BR). **c** Peak magnitude of shoulder extension acceleration before and after ball release, and peak magnitude of elbow acceleration and deceleration, both across subjects

was associated with the occurrence of a very small flexor muscle torque (Fig. 4b, arrow), and with onset of a large elbow flexor interaction torque (Fig. 4c). As the flexor interaction

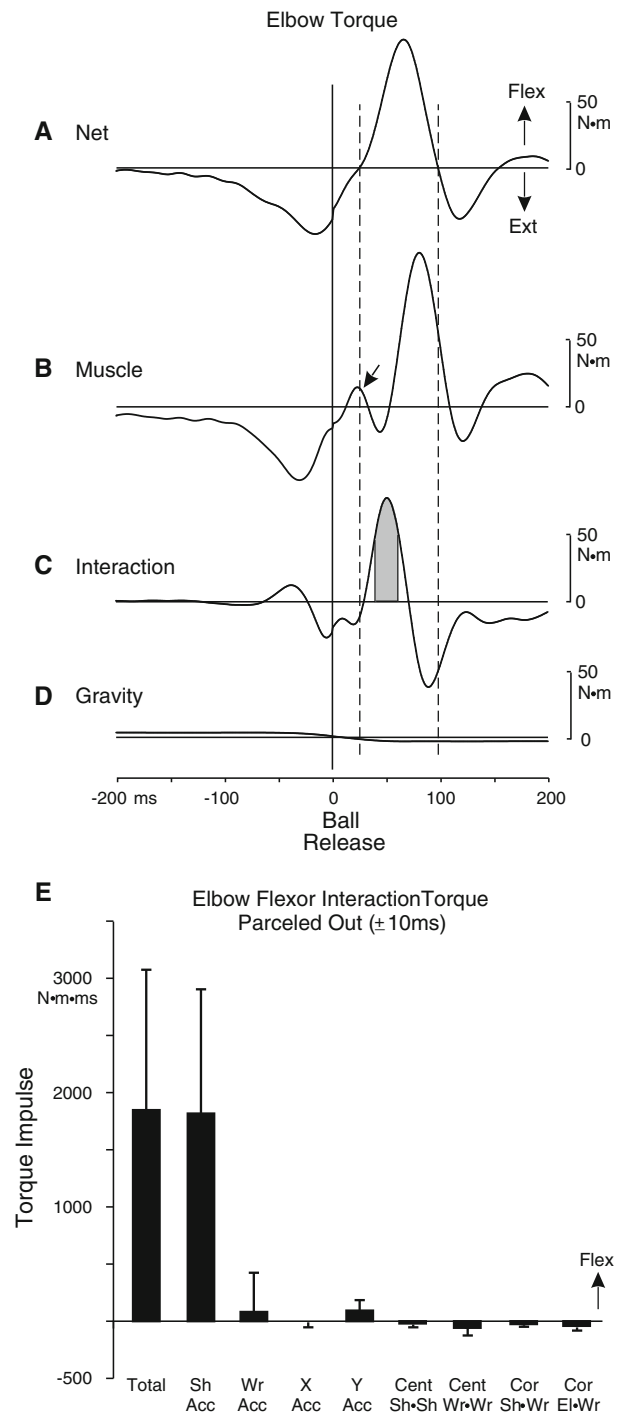


Fig. 4 a–d Computed elbow joint torques for same throws made by representative subject in Fig. 2. *Dashed lines* indicate period of elbow extension deceleration. **e** Parceled out elbow flexor interaction torque. Mean torque across subjects shown at *left* (Total). Each torque component integrated over ±10 ms period. *Bars* represent the means and SDs of 8 torque components: *ShAcc* shoulder acceleration, *WrAcc* wrist acceleration, *XAcc* horizontal translational acceleration of the origin of the arm model, *YAcc* vertical translational acceleration of the origin, *Cent Sh·Sh* centripetal effects from shoulder angular velocity, *Cent Wr·Wr* centripetal effects from wrist angular velocity, *Cor Sh·Wr* Coriolis effects associated with shoulder and wrist angular velocities, *Cor El·Wr* Coriolis effects from elbow and wrist angular velocities

torque decreased, the flexor muscle torque increased (Fig. 4b), which prolonged the flexor net torque and prolonged elbow deceleration.

Elbow deceleration (elbow flexor net torque) resulted from an elbow flexor interaction torque and an elbow flexor muscle torque in all subjects. In 11 of the 12 subjects, the major component of elbow flexor muscle torque came after the major component of elbow flexor interaction torque (as in Fig. 4). Although the elbow flexor interaction torque (Fig. 4c) was variable in magnitude from subject to subject, across subjects, its peak magnitude was large (mean 94 N m, SD 64). By comparison, across subjects, the peak magnitude of the late-occurring elbow flexor muscle torque (Fig. 4b) was mean 113 N m, SD 81. Across subjects, there was also variable occurrence of an early elbow flexor muscle torque (Fig. 4b, arrow). In 7 subjects, this contributed with the elbow flexor interaction torque to onset of the early elbow flexor net torque, whereas in five subjects it made no major contribution (as in Fig. 4b).

The elbow flexor interaction torque could arise from motion at the shoulder or from motion at the wrist or from both. One way to investigate this would be to integrate the elbow flexor interaction torque over its entire duration and parcel out its constituent components. However, because wrist acceleration showed rapid oscillations after ball release (Fig. 2c), we chose to integrate the elbow flexor interaction torque over a relatively narrow period with respect to its peak to minimize cancelation of interaction torque at the elbow arising from the oscillating wrist motion. Consequently, the elbow flexor interaction torque was measured by finding the time of its peak then integrating the torque over a period of ± 10 ms from this time for each throw in each subject. The gray area in Fig. 4c shows this period for the average tracing in the representative subject. Figure 4e—Total gives the mean and SD of this ± 10 ms elbow flexor interaction torque impulse averaged across subjects.

To determine the factors responsible for the elbow flexor interaction torque, we parceled out its individual components (Fig. 4e). The striking result is that across subjects almost the entire (total) elbow flexor interaction torque (1,847 N m s, SD 1,185) is accounted for by the component associated with shoulder extension acceleration (1,817 N m s, SD 1,138). Although in two subjects the component associated with wrist acceleration was quite large (up to 50% of the total elbow interaction torque), across subjects, this component was sometimes in the flexion direction and sometimes in the extension direction, which resulted in its cancelation when the mean across subjects was calculated (Fig. 4e, WrAcc). If direction is ignored across subjects, the absolute magnitude of the wrist acceleration component with respect to the total elbow interaction torque was only 15%. Either way, across subjects, the contribution from wrist acceleration

was not large. This is in keeping with the hierarchical feature that the distal wrist has a relatively weak effect on the proximal elbow (Dounskaia 2005). No other component associated with centripetal or Coriolis effects was of significant size.

In summary, in fast 2-D throws, elbow extension deceleration primarily resulted from two torques; an elbow flexor interaction torque that arose from follow-through shoulder extension acceleration and a late-occurring elbow flexor muscle torque.

Shoulder dynamics

Did the shoulder follow-through motion arise from shoulder muscle activity or from an interaction torque associated with elbow motion? To answer this question, we computed joint dynamics at the shoulder. Figure 5a–d shows time varying torques at the shoulder for the representative subject. Dashed lines represent onset and offset of elbow extension deceleration (as in Fig. 2). About 25 ms after ball release, a large shoulder net torque occurred in the extension direction (Fig. 5a). This net extensor torque was initiated by a shoulder extensor muscle torque (Fig. 5b, diagonal arrow). Across subjects, the shoulder extensor muscle torque after ball release was usually larger than that before ball release (in 10 subjects) and was variable in its timing with respect to ball release. In the representative subject, shortly after onset of this shoulder extensor muscle torque, there was onset of a shoulder extensor interaction torque (Fig. 5c), which maintained the shoulder net torque (Fig. 5a) in the extensor direction for the next 30 ms. This shoulder extension interaction torque occurred in all subjects and was large in size; across subjects, its mean magnitude was 244 N m, SD 104.

To determine the factors that contributed to the shoulder extension interaction torque, we parceled out its 9 constituent components. Each individual component was calculated for each trial of each subject then integrated over the ± 25 ms period around the peak of the total interaction torque for that trial. The gray area in Fig. 5c shows this period for the average. The mean integrated shoulder extensor interaction torque (torque impulse) across subjects is shown in Fig. 5e—Total. The parceled out components of the mean shoulder interaction torque across subjects are also shown in Fig. 5e. Almost the entire value of the total shoulder extensor interaction torque (mean 6,599 N m s, SD 2,163) is accounted for by the component associated with elbow extension deceleration (mean 6,817 N m s, SD 1,836).

In summary, during the period of elbow extension deceleration, there was a shoulder extensor net torque that was initiated by a shoulder extensor muscle torque and was maintained by a large shoulder extensor interaction torque which arose from elbow extension deceleration.

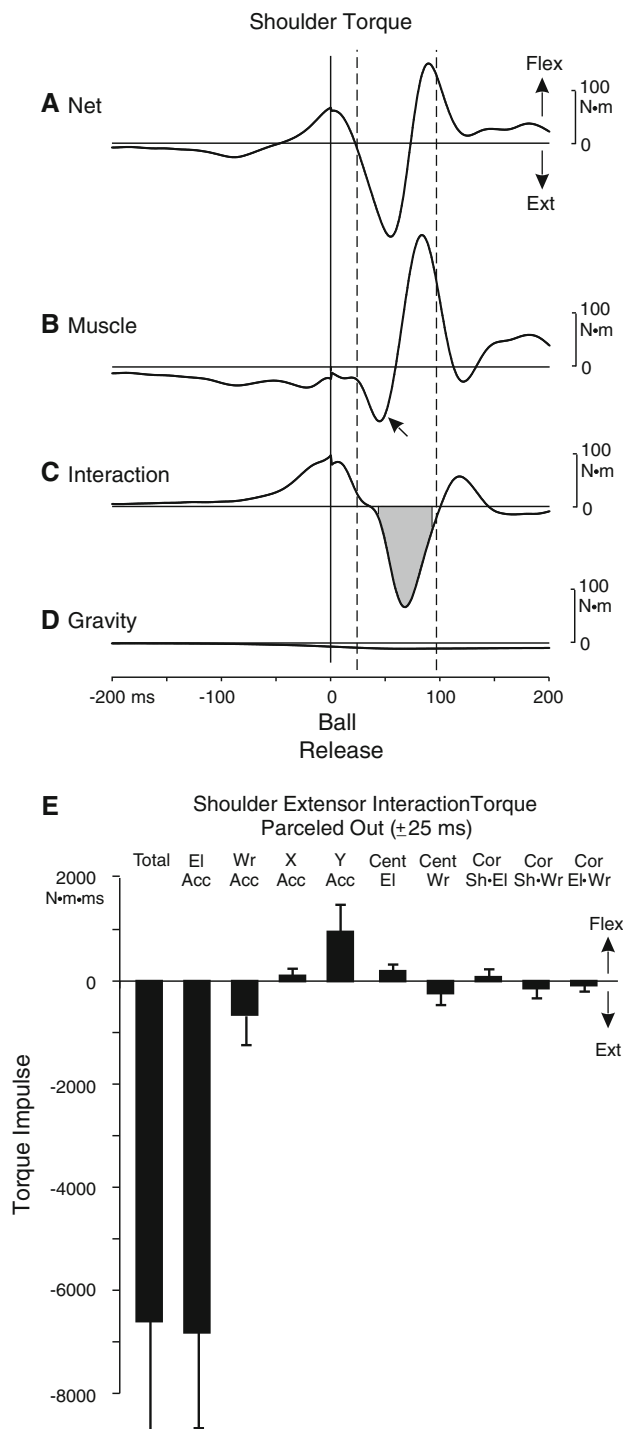


Fig. 5 Computed shoulder joint torques for the same throws shown in Figs. 2, 4. Dashed lines indicate period of elbow extension deceleration. E Parceled out shoulder extensor interaction torque. Mean torque across subjects shown at left (Total). Each torque component integrated over ± 25 ms period. Bars represent means and SDs of the 9 torque components: *ElAcc* elbow acceleration, *WrAcc* wrist acceleration, *XAcc* horizontal translational acceleration of origin of arm model, *YAcc* vertical translational acceleration of origin, *Cent El* centripetal effects from elbow angular velocity, *Cent Wr* centripetal effects from wrist angular velocity, *Cor Sh-El* Coriolis effects from shoulder and elbow angular velocities, *Cor Sh-Wr* Coriolis effects from shoulder and wrist angular velocities, *Cor El-Wr* Coriolis effects from elbow and wrist angular velocities

Overlap of shoulder and elbow interaction torques

The results so far indicate that during the period of elbow extension deceleration, shoulder motion produced an interaction torque that contributed to net flexor torque at the elbow, and elbow motion produced an interaction torque that contributed to net extensor torque at the shoulder. To gain insight into the cause and effect relationship between these torque events, we compared the timing of interaction torques at shoulder and elbow. To illustrate this comparison for the representative subject, torques at shoulder and elbow have been superimposed in Fig. 6. Although timing of the onset of elbow and shoulder interaction torques was slightly different, during the period of elbow extension deceleration, there was overlap of these two interaction torques (Fig. 6c, gray area). Such an overlap occurred in all subjects (mean duration of overlap 33 ms, SD 7).

One final point is that evidence was found for similarly timed braking commands from the CNS to the shoulder, elbow, and wrist muscles. The shoulder extensor follow-through motion was braked by a late occurring, shoulder flexor muscle torque (Fig. 6b), which peaked at about the same time after ball release as the elbow flexor muscle torque (Fig. 6b) (across subjects, shoulder peak mean 69 ms, SD 17, elbow peak mean 65 ms, SD 15). Although it was not the focus of the present study, we noticed that across subjects wrist muscle torque also peaked at a similar time, mean 67 ms, SD 13 (not shown). Comparison of the peak times for late-occurring shoulder, elbow, and wrist muscle torque revealed no statistically significant difference: one-way ANOVA [$F_{(2, 33)} = 0.173$, $P = 0.842$]. In summary, the elbow flexor interaction torque and the shoulder extensor interaction torque occurred simultaneously (overlapped) for an average period of 33 ms before being terminated by late-occurring shoulder flexor muscle torque.

Discussion

Mechanisms involved in the braking of elbow extension

The mechanisms that are involved in the braking of elbow extension in fast 2-D throws, and that were observed in all subjects, are summarized in Fig. 7. Elbow extension deceleration (Fig. 7a) is initiated by shoulder extensor muscle torque that produces shoulder extension acceleration which, in turn, produces elbow flexor interaction torque. Once the elbow begins to decelerate, a positive interaction loop occurs of passive torques between elbow and shoulder (Fig. 7b). Elbow extension deceleration is reinforced by a late, large, elbow flexor muscle torque (Fig. 7c). The positive interaction loop of passive torques is terminated by shoulder flexor muscle torque.

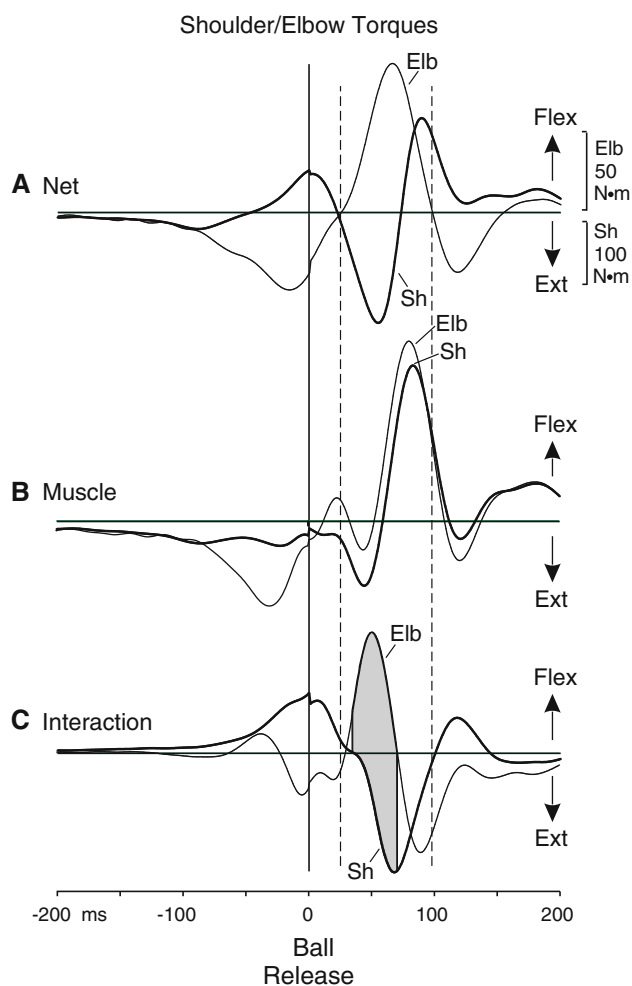


Fig. 6 Superimposed averages of shoulder (*thick traces*) and elbow (*thin traces*) for net, muscle, and interaction torque for representative subject. *Gray area*, overlap in time of elbow and shoulder interaction torque. *Dashed lines* indicate period of elbow extension deceleration

The above description reveals three features of shoulder-elbow coordination in the braking of elbow extension. The first is that, in agreement with the hypothesis, an interaction torque was utilized to decelerate (brake) elbow extension. Across subjects, elbow extension deceleration predominantly resulted from two torques that occurred in sequence: an elbow flexor interaction torque (Fig. 4c) followed by an elbow flexor muscle torque (Fig. 4b). These torques were large, overlapped, and added together to produce the large elbow deceleration.

A second feature was that the shoulder played two roles in braking elbow extension. The shoulder extensor muscles helped initiate the large shoulder extension acceleration and velocity after ball release (follow-through motion) (Figs. 2a, 3), which produced the elbow flexor interaction torque (Fig. 7a). In addition, the shoulder flexor muscles braked the shoulder follow-through motion, which was in part generated by the shoulder

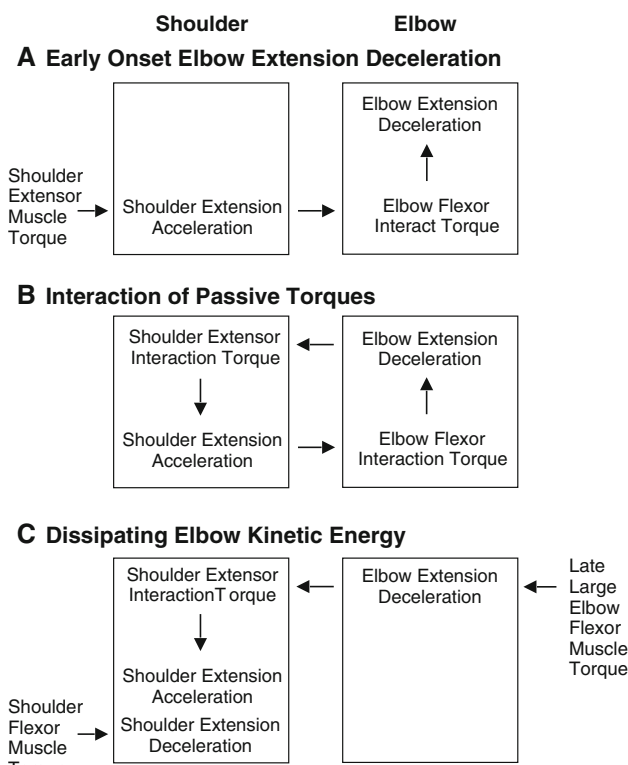


Fig. 7 Diagrammatic representation of the major factors occurring after ball release associated with **a** onset of elbow extension deceleration, **b** positive loop of interaction torques between shoulder and elbow, and **c** dissipating elbow kinetic energy

extensor interaction torque from elbow deceleration (Fig. 7c), i.e., shoulder flexors dissipated kinetic energy arising from elbow braking. These results are consistent with the leading-joint hypothesis (Dounskaia 2005, 2010) that proposes that joints of a multiarticular limb play different roles in movement, with motion of one leading joint generating powerful interaction torques at subordinate joints. For fast 2-D throws, the powerful shoulder musculature and the high inertia of the upper arm were used to generate an interaction torque for braking at the elbow (the subordinate joint). Considering the entire throw, previous and present results indicate that before ball release the elbow is the leading joint (Debicki et al. 2010), whereas after ball release the shoulder is the leading joint. One possibility is that this pattern results from the need for accuracy before ball release and the need for rapid braking after ball release.

Positive interaction loop of passive torques

A third feature of shoulder-elbow coordination in the braking of elbow extension is that the elbow flexor interaction torque was part of a positive interaction loop of passive

torques between elbow and shoulder (Fig. 7b). The time of occurrence of these torques overlapped in all subjects (mean overlap time 33 ms). These interaction torques did not arise from an alternating sequence of cause and effect mechanisms in which loop delay times occurred. Rather, in keeping with their origin in Newtonian mechanics, the mechanical positive effect of interaction torques between shoulder and elbow occurred instantaneously. One characteristic of this powerful positive interaction effect is that it was primarily due to inertial torques (which are proportional to acceleration/deceleration) rather than to velocity torques (which are proportional to the product of joint velocities). This was presumably because over the period of the elbow flexor interaction torque (Fig. 4c), shoulder velocity was not large, whereas shoulder extension acceleration (because it peaked earlier than shoulder velocity) was relatively large (Fig. 2a). Similarly, over the period of the shoulder extensor interaction torque (Fig. 5c), elbow velocity was initially large but decreased and reversed direction (Fig. 2b). Furthermore, elbow centripetal effects (velocity squared) produced a shoulder interaction torque in the flexor (not extensor) direction (Fig. 5e). In contrast, over the period of the shoulder extensor interaction torque (Fig. 5c), elbow deceleration was large (Figs. 2b, 3c).

Such mechanical positive effects of interaction torques were also found in these same subjects during elbow extension acceleration before ball release (Debicki et al. 2010). However, in this case, the effect was not as powerful, presumably because the shoulder has high inertia and, for motions before ball release, is only weakly affected by interaction torques from elbow motion (cf. Dounskaia 2005). In contrast, after ball release, shoulder motion was initially produced by both the powerful shoulder extensor musculature and the extensor interaction torque from elbow deceleration, and these effects added together. Mechanical positive effects of interaction torques may also occur in skilled fast baseball pitches. Feltner (1989) found that shoulder adduction deceleration produced an interaction torque that assisted elbow extension and that motion at the elbow produced an interaction torque that affected motion at the shoulder (see also Hong et al. 2001; Hirashima et al. 2008).

Central programming of elbow deceleration

Braking of elbow extension occurs by different mechanisms in different types of arm movements. In single joint movements, braking of elbow extension occurs by a largely centrally programmed phasic burst of elbow flexor (antagonist) muscle activity (as observed in the triphasic pattern of EMG activity, e.g., Cooke and Brown 1990; Berardelli et al. 1996; Gottlieb 1998). In contrast, in skilled 3-D overarm throws, evidence suggests that most braking of elbow extension comes from an interaction torque, which

appears to be associated with late-occurring shoulder rotation (Hong et al. 2001; Hore et al. 2005a). Muscle torque at the elbow plays an important role in the late stage of a skilled 3-D throw, but in stabilizing (clamping) rather than in braking. That is, in skilled 3-D throws after elbow extension deceleration, there was a 250 ms period of coactivation of large elbow flexor and elbow extensor EMG activity (Hore et al. 2005a). The present results show that 2-D throws lie somewhere between single joint elbow movement and skilled 3-D throwing in that braking of elbow extension occurs from both an interaction torque and an antagonist muscle torque.

One preliminary observation that may be relevant to the issue of the central programming of elbow braking in 2-D throws was that peak flexor muscle torque at elbow and shoulder (e.g., Fig. 6b), and peak extensor muscle torque at the wrist (not shown) occurred at similar latencies. Its role at elbow and shoulder was to brake and stabilize joint motion. Whether the similar timing of these muscle torques indicate an underlying control strategy akin to the linear synergy between shoulder and elbow (e.g., Gottlieb et al. 1996a, b) remains to be determined. Another observation for future investigation was that there was large variability from subject to subject in many of the measured parameters. One possibility is that subjects were not practiced at braking joint rotations in this task and were each using slightly different non-optimal techniques. One important parameter that showed variability was timing of onset of shoulder extensor muscle torque in the follow-through motion (Fig. 5b, diagonal arrow), which then resulted in variable shoulder and elbow kinetic parameters. Consequently, one future objective should be to determine the optimal torque pattern for producing fast ball speeds and efficient braking in 2-D throws and to determine how it develops with practice. Another future objective of interest would be to determine whether the dominant arm has a significant advantage over the nondominant arm in the utilization of interaction torques for braking (cf. Sainburg and Kalakanis 2000; Bagesteiro and Sainburg 2003; Hore et al. 2005b).

Conclusion

It is concluded for fast 2-D throws, that in keeping with the hypothesis, the CNS deliberately utilized powerful interaction torques between shoulder and elbow to brake motion at the elbow. This was achieved by the generation of shoulder extensor muscle torque after ball release that produced a rapid shoulder follow-through motion.

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References

- Bagesteiro LB, Sainburg RL (2003) Nondominant arm advantages in load compensation during rapid elbow joint movements. *J Neurophysiol* 90:1503–1513
- Bastian AJ, Martin TA, Keating JG, Thach WT (1996) Cerebellar ataxia: abnormal control of interaction torques across multiple joints. *J Neurophysiol* 76:492–509
- Bastian AJ, Zackowski KM, Thach WT (2000) Cerebellar ataxia: torque deficiency or torque mismatch between joints? *J Neurophysiol* 83:3019–3030
- Berardelli A, Hallett M, Rothwell JC, Agostino R, Manfredi M, Thompson PD, Marsden CD (1996) Single-joint rapid arm movements in normal subjects and in patients with motor disorders. *Brain* 119:661–674
- Buchanan JJ (2004) Learning a single limb multijoint coordination pattern: the impact of a mechanical constraint on the coordination dynamics of learning and transfer. *Exp Brain Res* 156:39–54
- Cooke JD, Brown SH (1990) Movement-related phasic muscle activation. II. Generation and functional role of the triphasic pattern. *J Neurophysiol* 63:465–472
- Cooper SE, Martin JH, Ghez C (2000) Effects of inactivation of the anterior interpositus nucleus on the kinematic and dynamic control of multijoint movement. *J Neurophysiol* 84:1988–2000
- de Rugy A, Riek S, Carson RG (2006) Influence of predominant patterns of coordination on the exploitation of interaction torques in a two-joint rhythmic arm movement. *Exp Brain Res* 175:439–452
- Debicki DB, Gribble PL (2004) Inter-joint coupling strategy during adaptation to novel viscous loads in human arm movement. *J Neurophysiol* 92:754–765
- Debicki DB, Gribble PL, Watts S, Hore J (2004) Kinematics of wrist joint flexion in overarm throws made by skilled subjects. *Exp Brain Res* 154:382–394
- Debicki DB, Watts S, Gribble PL, Hore J (2010) A novel shoulder-elbow mechanism for increasing speed in a multijoint arm movement. *Exp Brain Res* 203:601–613
- Dounskaia N (2005) The internal model and the leading joint hypothesis: implications for control of multi-joint movements. *Exp Brain Res* 166:1–16
- Dounskaia N (2010) Control of human limb movements: the leading joint hypothesis and its practical applications. *Exerc Sport Sci Rev* 38:201–208
- Dounskaia NV, Swinnen SP, Walter CB, Spaepen AJ, Verschueren SM (1998) Hierarchical control of different elbow-wrist coordination patterns. *Exp Brain Res* 121:239–254
- Dounskaia N, Van Gemmert AW, Stelmach GE (2000) Interjoint coordination during handwriting-like movements. *Exp Brain Res* 135:127–140
- Dounskaia N, Ketcham CJ, Stelmach GE (2002) Commonalities and differences in control of various drawing movements. *Exp Brain Res* 146:11–25
- Feltner ME (1989) Three-dimensional interactions in a two-segment kinetic chain. Part II. Application to the throwing arm in baseball pitching. *Int J Sport Biomech* 5:420–450
- Furuya S, Kinoshita H (2008) Organization of the upper limb movement for piano key-depression differs between expert pianists and novice players. *Exp Brain Res* 185:581–593
- Galloway JC, Koshland GF (2002) General coordination of shoulder, elbow and wrist dynamics during multijoint arm movements. *Exp Brain Res* 142:163–180
- Gottlieb GL (1998) Muscle activation patterns during two types of voluntary single-joint movement. *J Neurophysiol* 80:1860–1867
- Gottlieb GL, Song Q, Hong D-A, Almeida GL, Corcos D (1996a) Coordinating movements at two joints: a principle of linear covariance. *J Neurophysiol* 75:1760–1764
- Gottlieb GL, Song Q, Hong D-A, Corcos DM (1996b) Coordinating two degrees of freedom during human arm movement: load and speed invariance of relative joint torques. *J Neurophysiol* 76:3196–3206
- Gray S, Watts S, Debicki D, Hore J (2006) Comparison of kinematics in skilled and unskilled arms of the same recreational baseball players. *J Sports Sci* 24:1183–1194
- Gribble PL, Ostry DJ (1999) Compensation for interaction torques during single- and multijoint limb movement. *J Neurophysiol* 82:2310–2326
- Hirashima M, Kudo K, Ohtsuki T (2003) Utilization and compensation of interaction torques during ball-throwing movements. *J Neurophysiol* 89:1784–1796
- Hirashima M, Kudo K, Watarai K, Ohtsuki T (2007) Control of 3D limb dynamics in unconstrained overarm throws of different speeds performed by skilled baseball players. *J Neurophysiol* 97:680–691
- Hirashima M, Yamane K, Nakamura Y, Ohtsuki T (2008) Kinetic chain of overarm throwing in terms of joint rotations revealed by induced acceleration analysis. *J Biomech* 41:2874–2883
- Hollerbach MJ, Flash T (1982) Dynamic interactions between limb segments during planar arm movement. *Biol Cybern* 44:67–77
- Hong D-A, Cheung TK, Roberts EM (2001) A three-dimensional, six-segment chain analysis of forceful overarm throwing. *JEMG Kinesiol* 11:95–112
- Hore J, Watts S, Tweed D (1996) Errors in the control of joint rotations associated with inaccuracies in overarm throws. *J Neurophysiol* 75:1013–1025
- Hore J, Watts S, Tweed D (1999) Prediction and compensation by an internal model for back forces during finger opening in an overarm throw. *J Neurophysiol* 82:1187–1197
- Hore J, Debicki DB, Watts S (2005a) Braking of elbow extension in fast overarm throws made by skilled and unskilled subjects. *Exp Brain Res* 164:365–375
- Hore J, O'Brien M, Watts S (2005b) Control of joint rotations in overarm throws of different speeds made by dominant and nondominant arms. *J Neurophysiol* 94:3975–3986
- Koshland GF, Galloway JC, Nevoret-Bell CJ (2000) Control of the wrist in three-joint arm movements to multiple directions in the horizontal plane. *J Neurophysiol* 83:3188–3195
- Lee G, Fradet L, Ketcham CJ, Dounskaia N (2007) Efficient control of arm movements in advanced age. *Exp Brain Res* 177:78–94
- Pigeon P, Bortolami SB, DiZio P, Lackner JR (2003) Coordinated turn-and-reach movements. I. Anticipatory compensation for self-generated Coriolis and interaction torques. *J Neurophysiol* 89:276–289
- Putnam CA (1993) Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *J Biomech* 26(Suppl 1):125–135
- Sainburg RL, Kalakanis D (2000) Differences in control of limb dynamics during dominant and nondominant arm reaching. *J Neurophysiol* 83:2661–2675
- Schneider K, Zernicke RF, Schmidt RA, Hart TJ (1989) Changes in limb dynamics during the practice of rapid arm movements. *J Biomech* 22:805–817
- Sorensen H, Zacho M, Simonsen EB, Dyhre-Poulsen P, Klausen K (1996) Dynamics of the martial arts high front kick. *J Sports Sci* 14:483–495
- Tweed D, Cadera W, Vilis T (1990) Computing three-dimensional eye position quaternions and eye velocity from search coil signals. *Vision Res* 30:97–110
- Winter D (2005) *Biomechanics and motor control of human movement*. Wiley, Hoboken