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RESEARCH ARTICLE

A novel shoulder–elbow mechanism for increasing speed in a multijoint arm movement

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Abstract The speed of arm movements is normally increased by increasing agonist muscle activity, but in overarm throwing, an additional effect on speed may come from exploitation of interaction torques (a passive torque associated with motion at adjacent joints). We investigated how the central nervous system (CNS) controls interaction torques at the shoulder and elbow to increase speed in 2-D overarm throwing. Twelve experienced throwers made slow, medium, and fast 2-D throws in a parasagittal plane. Joint motions were computed from recordings made with search coils; joint torques were calculated using inverse dynamics. For slow and medium-speed throws, elbow extension was primarily produced by elbow muscle torque. For fast throws, there was an additional late-occurring elbow extensor interaction torque. Parceling out this elbow extension interaction torque revealed that it primarily arose from shoulder extension deceleration. Surprisingly, shoulder deceleration before ball release was not caused by shoulder flexor (antagonist) muscle torque. Rather, shoulder deceleration was produced by passive elbow-to-shoulder interaction torques that were primarily associated with elbow extension acceleration and velocity. It is concluded that when generating fast 2-D throws, the CNS utilized the arm's biomechanical properties to increase ball speed. It did this by coordinating shoulder and elbow motions such that an instantaneous mechanical positive feedback occurred of interaction torques between shoulder and elbow before ball release. To what extent this mechanism is utilized in other fast multijoint arm movements remains to be determined.

Keywords Interaction torque · Overarm throwing · Speed · Inverse dynamics · Coordination · Central nervous system · Human

Introduction

Subjects can generate arm movements at different speeds, but how the nervous system plans and coordinates shoulder and elbow motion to achieve this is unclear. Arm movements are influenced by interaction torques, which arise at one joint due to the rotation of adjacent joints (Hollerbach and Flash 1982). For example, the rotation of the proximal shoulder joint influences the motion of distal elbow and wrist joints through interaction torques in the proximal-to-distal direction (Almeida et al. 1995; Latash et al. 1995; Dounskaia et al. 1998, 2002; Gribble and Ostry 1999; Levin et al. 2001; Galloway and Koshland 2002; Buchanan 2004). Similarly, rotation of distal joints can influence proximal joint motion. For example, during elbow flexion, there was a distal-to-proximal interaction torque at the shoulder (Almeida et al. 1995; Gottlieb et al. 1996; Gribble and Ostry 1999; Debicki and Gribble 2004, 2005). And during paw-shaking in the cat, interaction torques occurred at the hip and knee joints (Hoy et al. 1985; Smith et al. 1985; Hoy and Zernicke 1986).

It is generally believed that the nervous system accounts for interaction torques in the motor plan by predictive mechanisms that involve an internal model of limb and

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movement dynamics. Such mechanisms allow the nervous system to compensate for interaction torques in situations which might result in a perturbation of the desired motion (e.g., Gribble and Ostry 1999). Alternatively, these mechanisms also allow the nervous system to exploit interaction torques (Bernstein 1967; Schneider et al. 1989; Hirashima et al. 2003; Dounskaia 2005).

Overarm throwing is a challenging task for the motor system, as it requires the coordination of multiple joints (shoulder, elbow, and wrist) to generate high ball speeds with high spatial precision at ball release (e.g., Timmann et al. 1999; Hore and Watts 2005). Hirashima et al. (2003) demonstrated that for 2-D overarm throwing, interaction torque arising from shoulder motion was utilized to generate elbow extension velocity in fast throws. That is, the role of the initial shoulder extension muscle torque was not only to accelerate the shoulder in the forward direction, but also to produce an assistive interaction torque at the elbow. One possibility is that this interaction torque was dependent on the velocity of motion at the proximal joint (cf. Hirashima et al. 2003; Putnam 1993). An alternative possibility is that the interaction torque at the elbow arises from shoulder extension deceleration (cf. Herring and Chapman 1992). In keeping with this, Hirashima et al. (2003) showed that shoulder deceleration occurred before ball release. One surprising finding was that shoulder deceleration was associated with a flexor interaction torque at the shoulder. This presumably was a distal-to-proximal interaction torque arising from rotation of the forearm about the elbow joint.

These pioneering findings of Hirashima et al. (2003) have led to two unresolved questions. First, what is the origin of the proximal-to-distal interaction torque at the elbow, i.e., is it velocity dependent, or acceleration dependent, or both? Second, what effect does rotation at the elbow have on the shoulder and how does this contribute to the overall throwing motion?

The goal of the present study was to investigate how the nervous system coordinates joint torque arising from interaction torques to generate fast 2-D throws. The specific objective was to determine the nature and role of proximal-to-distal interaction torques at the elbow from shoulder motion and distal-to-proximal interaction torques at the shoulder from elbow motion, in the production of fast 2-D overarm throws. To achieve this goal, we extended the work of Hirashima et al. (2003) by decomposing interaction torques at shoulder and elbow (both early and late) into their constituent components. The results show that interaction torques at the elbow are primarily acceleration dependent and that in fast throws, elbow and shoulder rotations initiate a mechanical positive feedback of interaction torques at shoulder and elbow which produces a second increase in elbow extension velocity before ball release.

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. All were right-handed skilled recreational throwers. Subjects made 2-D throws from a sitting position with the trunk constrained from moving forward by means of straps pulled tightly over the shoulders. This minimized but did not eliminate forward trunk motion (see later). Consequently, trunk motion was taken into account in data analysis. The participants were instructed to throw accurately using a baseball (150 gm). Two-dimensional throws were made in the following order: 20 slow, 20 medium, 20 fast, and 20 medium. Only the first three sets of throws were analyzed in detail. For the medium speeds, subjects were instructed to use a 2-D overarm motion (keeping the elbow in the vertical plane), to throw at a comfortable speed, and to throw accurately; for the slow throws, the instruction was the same, but to throw more slowly than the medium speeds (which had been established in practice throws). However, to investigate shoulder and elbow interactions, we needed to be sure that subjects understood that they could utilize shoulder rotation. Consequently, for the fast throws, subjects were instructed to throw as fast as possible and accurately and that they were free if they wished to increase the amplitude of shoulder motion by increasing the backswing (shoulder flexion). Subjects were allowed practice throws until they were comfortable at all instruction speeds. Subjects were instructed to keep the arm in a parasagittal (vertical) plane. An experimenter standing behind the subject reported if the elbow came out of the plane and these throws were excluded. Planarity was also verified 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 for 95% of throws which is given by SD × 3.92. On average, 18 slow, 18 medium, and 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 finger was measured with a pressure-sensitive microswitch that was attached to the distal phalanx of the middle finger. The participants were instructed to grip the ball so that it rolled over the distal switch. The timing accuracy of the distal microswitch was verified by comparing it with the time of onset of finger 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. 1996, 1999). Ball speed was measured with a radar gun (Stalker Professional Sports Radar, sampling rate 100 Hz), which 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 (e.g., Hore et al. 1996, 1999). 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 three orthogonal alternating magnetic fields of frequency 62.5, 100, and 125 kHz generated by 3 × 3 × 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 (Tweed et al. 1990). 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. Joint angular velocities and accelerations were obtained by differentiation. Shoulder, elbow, and wrist joint kinematics were low-pass filtered using a second-order Butterworth filter at 20, 30, and 45 Hz, respectively, using Matlab (The Mathworks). At the start of each experiment, a calibration was performed in which the upper arm was rotated 90° to the front and the forearm pronated such that the forearm, hand, and fingers were in a vertical line with the palm facing forward. This position was used as the reference position in the kinematic figure (Fig. 2). For the equations of motion, we used the convention described by Hirashima et al. (2003).

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 model included translational shoulder motion to account for the small trunk motion. Shoulder joint angle ($\theta 1$) was defined relative to the vertical axis passing through the shoulder joint (i.e., the origin of the arm model labeled O in Fig. 1), elbow joint angle ($\theta 2$) was defined relative to the long axis of the upper arm, and wrist joint angle ($\theta 3$) was defined relative to the long axis of the forearm. Positive joint angles were in the counterclockwise (upwards) direction (shoulder flexion, elbow flexion, and wrist extension). 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 (Northern Digital, Inc.) at 500 Hz. 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. This measure of forward–back and up–down motion of the proximal part of the arm model represents the net motion of all body parts proximal to the arm, including rotation and translation of the trunk (Hirashima et al. 2003). 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. 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. Only those torques associated with the shoulder and elbow joints are reported here. Torque variables were defined according to previous studies (e.g., Debicki and Gribble 2004; Hirashima et al. 2003; Gribble and Ostry 1999; Bastian et al. 1996, 2000; Cooper et al. 2000; Hollerbach and Flash 1982) where the NET torque is defined as the sum of the other components (NET = MUS + INT + GRA) and where the MUS torque parameter is computed as a residual value (MUS = NET − INT − 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 muscle and other joint tissues.

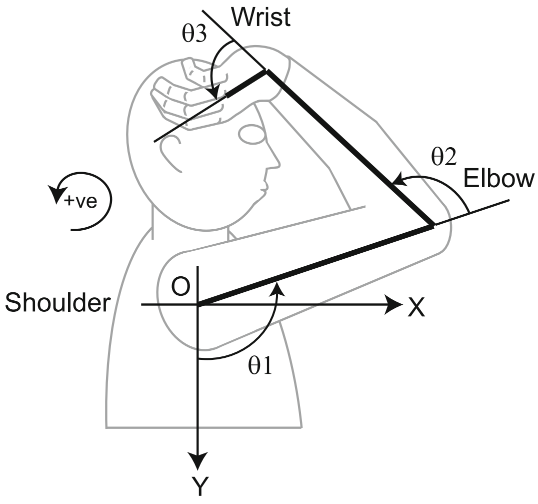

Fig. 1 Joint angles in the 3-joint throwing task

To quantify the computed joint dynamics, net, muscle, interaction, and gravity torques were integrated over various time windows for each individual throw to compute a torque impulse for each torque parameter which was then averaged across throwing speeds and across subjects. The elbow interaction torque consisted of eight motion-dependent component variables: an inertial torque dependent on the angular acceleration of the shoulder joint, an inertial torque dependent on the angular acceleration of the wrist joint, an inertial torque dependent on the linear (forward–back) acceleration of the origin of the model, an inertial torque dependent on the linear (up–down) acceleration of the origin of the model, two centripetal torques dependent on the squared angular velocity of the shoulder joint and wrist joint, respectively, and two Coriolis torques dependent on the product of shoulder joint and wrist joint angular velocity and on the product of elbow joint and wrist joint velocity.

Shoulder joint dynamics were also quantified by integrating net, muscle, interaction, and gravity torque over time. The shoulder interaction torque was composed of nine motion-dependent variables: an inertial torque dependent on the angular acceleration of the elbow joint, an inertial torque dependent on the angular acceleration of the wrist joint, an inertial torque dependent on the translational (forward–back) acceleration of the origin of the model, an inertial torque dependent on the translational (up–down) acceleration of the origin of the model, two centripetal torques dependent on the squared angular velocity of the elbow joint and wrist joint, respectively, and three Coriolis torques dependent on the product of shoulder joint and elbow joint angular velocity, on the product of shoulder joint and wrist joint velocity, and on the product of elbow joint and wrist joint velocity.

Statistics

The effect of throwing speed on different parameters was assessed with one-way repeated-measures ANOVAs. Post hoc analyses were performed with the Tukey test, with statistical significance set at $P < 0.05$. This is indicated by asterisks in the figures.

Results

Subjects threw baseballs in a sagittal plane from a sitting position at slow, medium, and fast speeds. Across subjects, the mean ball speeds for slow (S), medium (M), and fast (F) throws were 28.1 km/h (SD 2.7), 33.8 (1.8), and 44.6 (4.0). There was a main effect of throwing speed instruction on ball speed (repeated-measures ANOVA, $P < 0.001$). A post hoc analysis (Tukey test, $P < 0.05$) showed significant differences between each throwing speed condition.

Joint kinematics

Angular kinematics of joint rotations from a representative subject (Pc) are shown as a function of time in Fig. 2. Each trace represents the mean of 20 throws for the shoulder, elbow, and wrist joints during slow (thick traces), medium (medium traces), and fast (thin traces) throws. All traces are aligned on the point in the throw when the ball was released from the hand (time 0). Figure 2a shows that the throwing motion consisted of an initial backswing (up-going traces) that was produced by shoulder flexion. This was followed by a period of shoulder extension, i.e., forward rotation (down-going traces). Shoulder extension was initially accompanied by elbow flexion (Fig. 2d, up-going trace), and then by elbow extension. The onsets of joint rotations in the forward direction were sequential: the onset of shoulder extension (Fig. 2a) began 200–250 ms before ball release, the onset of elbow extension (Fig. 2d) about 100 ms before ball release, and the onset of wrist flexion (Fig. 2g) about 50 ms before ball release. As expected from the instructions to the subject, fast throws had a larger shoulder extension amplitude to ball release (i.e., the angular distance from the forward starting position to the position at ball release was larger for fast throws; Fig. 2a). This finding was consistent across subjects and was due to a more flexed shoulder starting position. In contrast, at the time of ball release, the amplitude of elbow extension (Fig. 2d) and the positions of the shoulder (Fig. 2a) and elbow (Fig. 2d) were relatively consistent across throwing speeds. After ball release, all joints continued to rotate in the forward direction.

Figure 3 shows that across subjects, shoulder peak extension velocity was greater for fast throws than for slow or medium-speed throws (Fig. 3a) [$F(1,14) = 31.0$, $P < 0.001$], as it was for shoulder peak extension acceleration (Fig. 3c) [$F(1,12) = 31.0$, $P < 0.001$]. Elbow peak extension velocity increased with each increase in throwing speed (Fig. 3b) [$F(2,22) = 60.0$, $P < 0.001$], as did elbow peak extension acceleration (Fig. 3d) [$F(1,12) = 32.3$, $P < 0.001$].

All subjects showed a period of shoulder extension deceleration before ball release like that shown for the representative subject in Fig. 2c, up-going trace. There was also a second period of shoulder deceleration after ball release which was associated with terminating shoulder extension. The representative subject had a peak value of shoulder extension deceleration (Fig. 2c, up-going trace) prior to ball release that was greater in magnitude for fast throws compared to slow and medium-speed throws. Similarly, across subjects, there was an effect of throwing speed on the magnitude of the peak shoulder angular deceleration (Fig. 3e) [$F(2,22) = 38.4$, $P < 0.001$]. Post hoc Tukey tests

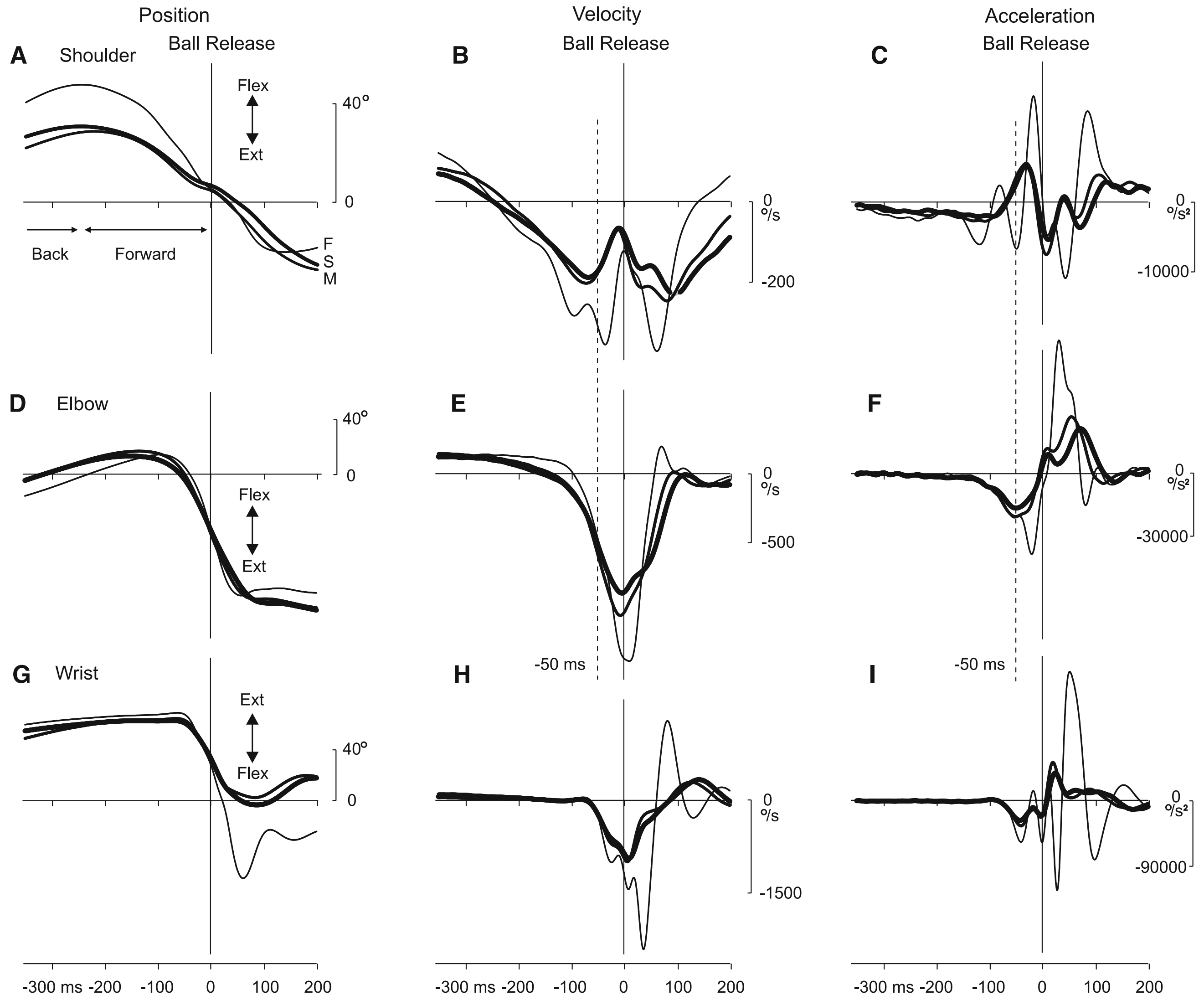

Fig. 2 Average angular kinematics of joint rotations from a representative subject (Pc). **a**, **d**, **g** joint angular positions; **b**, **e**, **h** joint angular velocities; **c**, **f**, **i** joint angular accelerations for the shoulder, elbow, and wrist joints. Each *trace* represents the average of 20 throws for slow (*thick traces*), medium (*medium traces*), and fast throws (*thin traces*), aligned on the time of ball release (*solid vertical line*, 0 ms). Bidirectional *vertical arrows* indicate the direction of rotation for each joint. *Horizontal arrows* in **a** indicate backward and forward shoulder motion to ball release. Zero angular position in **a**, **d**, **g** gives reference position (see section "Methods"). *Vertical dashed lines* indicate 50 ms before ball release

showed that shoulder deceleration increased with each increase in throwing speed.

In summary, the 2-D overarm throwing motion was sequential in nature, an increase in throwing speed was associated with an increase in angular extension acceleration and velocity of the shoulder and elbow joints, and the shoulder extension deceleration prior to ball release increased in magnitude for fast throws.

Elbow dynamics

To determine the role of proximal-to-distal interaction torques at the elbow arising from shoulder motion in generating elbow extension prior to ball release, shoulder and elbow dynamics were computed using inverse dynamics. The computed elbow joint torques for subject Pc are shown in Fig. 4 as a function of time. Each trace represents the average of 20 throws for the slow (thick traces), medium speed (medium traces), and fast (thin traces) throws. Figure 4a shows that the majority of the difference in net elbow extension torque between medium and fast speeds occurred late in the throw, but before ball release. About 40 ms before ball release (dashed line is at −50 ms), elbow net torque was in the extension direction for all speeds and there was little difference between speeds. However, after this time, there was a marked increase in the net torque in

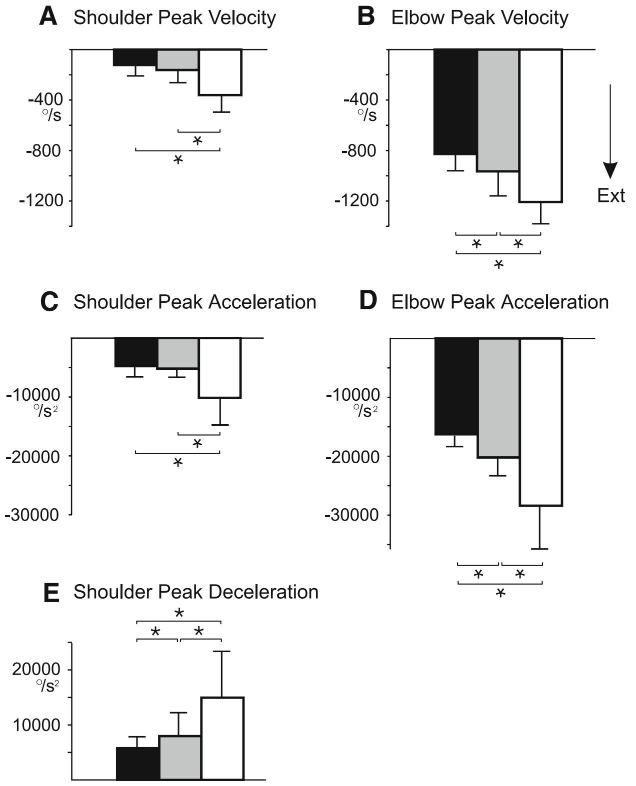

Fig. 3 Means and SDs of shoulder and elbow joint angular kinematic parameters across subjects for slow (S, *black bars*), medium (M, *gray bars*), and fast throws (F, *open bars*). **a**, **b** joint angular velocities; **c**, **d** joint angular accelerations; e shoulder joint angular deceleration. * $P < 0.05$ (post hoc Tukey test)

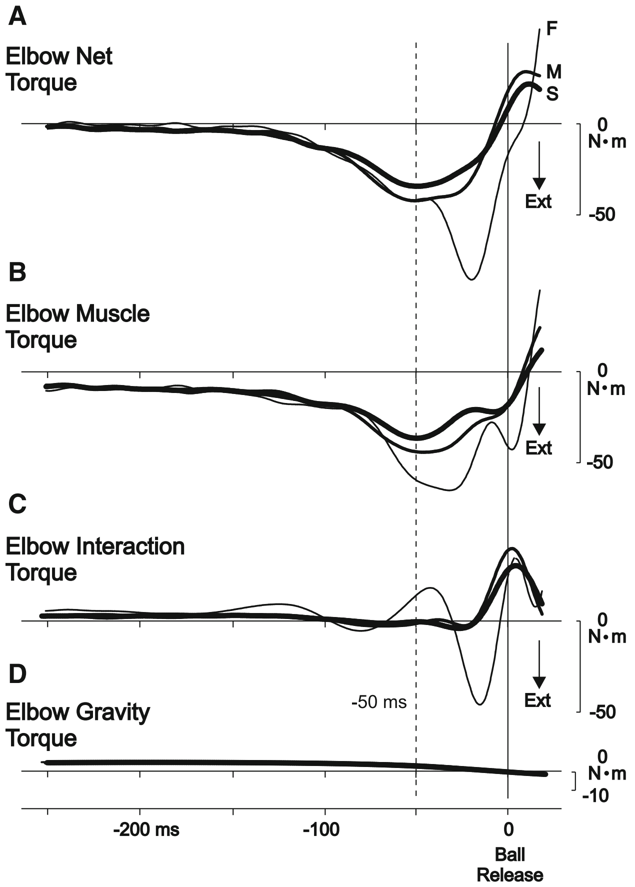

Fig. 4 Computed elbow joint torques from a representative subject (Pc). Each *trace* represents the average of 20 throws for slow (S, *thick traces*), medium (M, *medium traces*), and fast throws (F, *thin traces*), aligned on time of ball release (*solid vertical line*, 0 ms). *Vertical arrow* indicates the direction of elbow extension

the fast throws which peaked about 20 ms before ball release. The early period of net extensor torque (before this late increase) was related to muscle torque (Fig. 4b), which counteracted two torques that acted in the flexor direction: early interaction torque (Fig. 4c) and gravity (Fig. 4d). For the fast throws, the late increase in elbow extensor interaction torque (Fig. 4c) enabled the elbow net torque (Fig. 4a) to increase at a time when muscle torque (Fig. 4b) had plateaued and was starting to decrease.

At the elbow, the individual torque components were integrated to determine the relative contributions that each had on the elbow extensor net torque during the forward throw. Given that elbow extension acceleration (Fig. 2f) and elbow net torque (Fig. 4a) lasted for about 100 ms, and in fast throws had a second increase at about 50 ms before ball release, we integrated over two different periods. Integrating from 100 to 50 ms before ball release (when the net torque was in the extension direction) demonstrated that, across subjects, the elbow extensor net torque (Fig. 5A) was produced by elbow extensor muscle torque (Fig. 5B). This was because the integrated interaction torque (Fig. 5C) and the integrated gravity torque (Fig. 5D) were small and in the flexor direction. No reliable difference between throwing speeds was found for the integrated net, muscle, or interaction torque.

We also integrated over the period from 50 ms before ball release to ball release (when net torque was in the extensor direction). Over this late integration period, across subjects, the extensor net torque for fast throws (open bar, Fig. 5E) was produced by a combination of extensor muscle torque (Fig. 5F) and extensor interaction torque (Fig. 5G). In contrast, the extensor net torques for slow and medium-speed throws were produced primarily by muscle torque since the interaction torque for these throws continued to be in the flexor direction. The repeated-measures ANOVAs for these increases in torque with an increasing throwing speed were net torque (Fig. 5E) [$F(1,12) = 48.0$, $P < 0.001$], muscle torque (Fig. 5F) [$F(1,11) = 13.5$, $P = 0.003$], and interaction torque (Fig. 5G) [$F(1,12) = 17.4$, $P = 0.001$].

For fast throws, the late extensor muscle torque (Fig. 5F) accounted for approximately 80% of the late extensor net torque (Fig. 5E), whereas the late extensor interaction torque (Fig. 5G) accounted for approximately

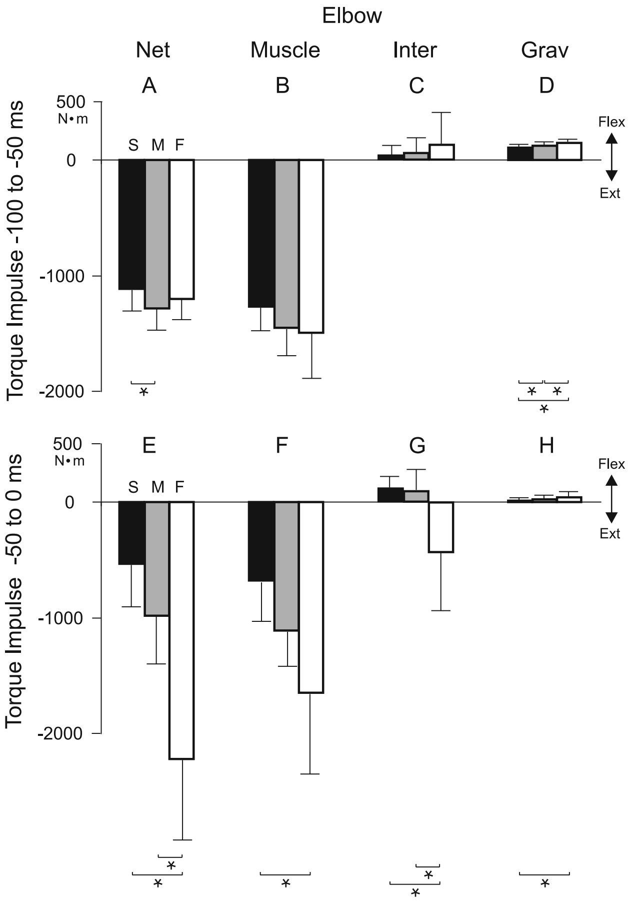

Fig. 5 Means and SDs of integrated elbow torque across subjects for slow (*black bars*), medium (*gray bars*), and fast throws (*open bars*). *A–D* integrated elbow torque over -100 to -50 ms period before ball release when net torque was in extension direction. *E–H* same over -50 ms to ball release (0 ms) period. $*P < 0.05$ (post hoc Tukey test)

20% of the net torque. Although the late elbow extensor interaction torque did not make a large contribution to the late elbow net torque for fast throws, it made a significant contribution to the increase in net torque when comparing medium and fast throws. Whereas the difference in the net elbow extensor torque (Fig. 5E) when going from slow to the medium speed was associated with a 93% contribution from elbow muscle torque (Fig. 5F), (and a 7% decrease in elbow flexor interaction torque), the difference in extensor net torque (Fig. 5E) when going from medium to fast throws was associated with an ~50% contribution from elbow extensor muscle torque (Fig. 5F) and a 50% contribution from elbow extensor interaction torque (Fig. 5G).

In summary, although in fast throws the late elbow extensor interaction torque was not large when compared to the late elbow extensor net torque, it made a significant (~50%) contribution to the change in the late elbow extensor net torque when going from medium to fast throws.

Parceling out the elbow interaction torque

To determine the source of the late extensor interaction torque at the elbow, we parceled out its individual components. Each component was calculated, and then integrated for each individual throw over the same 50-ms integration period used to calculate the late interaction torque in Fig. 5G. The integrated interaction torque components, averaged across subjects, are shown in Fig. 6 for the slow, medium, and fast throws. The late elbow extensor interaction torque values (the same values as Fig. 5G) are shown in Fig. 6A. The largest contribution to the late elbow extension interaction torque came from shoulder extension deceleration (Fig. 6B). This component of the extensor interaction torque was greater in magnitude for fast throws than for slow or medium speed throws [$F(1,12) = 21.1$, $P < 0.001$]. The components associated with the linear acceleration of the origin of the arm model also acted in the direction of elbow extension but they were relatively small (Fig. 6D, E). Other components were either small (Fig. 6F) or acted in the flexion direction (Fig. 6C, G–I).

In summary, parceling out the late elbow extension interaction torque for the fast throws revealed that the primary contribution came from shoulder deceleration.

Shoulder dynamics

What caused the shoulder to decelerate prior to ball release? To determine the role of distal-to-proximal interaction torques at the shoulder, shoulder joint dynamics were computed. The mean time-varying joint torques at the shoulder joint for the representative subject are shown in Fig. 7: slow (thick traces), medium speed (medium traces), and fast throws (thin traces). Considering the fast throws, in keeping with kinematic records (Fig. 2c), which showed two periods of early shoulder extension acceleration before ball release, shoulder net torque (Fig. 7a) and shoulder muscle torque (Fig. 7b) also showed two periods of early torque in the extension (downward) direction. This association between shoulder extensor net torque and shoulder extensor muscle torque was found across subjects.

Shoulder extension deceleration was caused by the net flexor torque (up-going traces, Fig. 7a). For the representative subject, the late shoulder net torque in the flexor direction before ball release (Fig. 7a, downward arrow) did not arise from shoulder muscle torque (Fig. 7b) or from the gravity torque (Fig. 7d). Rather, the late shoulder flexor net torque (Fig. 7a, downward arrow) resulted from a late shoulder interaction torque in the flexion direction (Fig. 7c). Early in the throw, the small magnitude of the flexor interaction torque (Fig. 7c) was overcome by extensor muscle torque (Fig. 7b) which enabled shoulder extension motion to occur. For the fast throws, it was not until

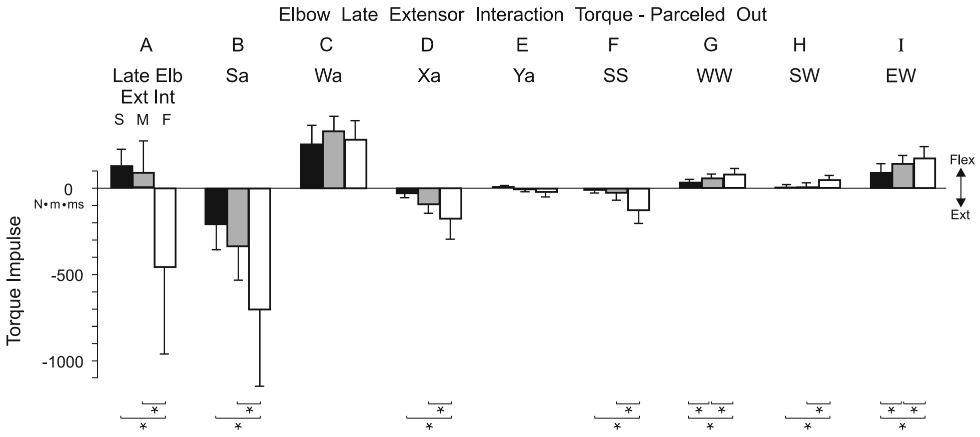

Fig. 6 Parceled out late elbow extensor interaction torque. *Bars* represent the means and SDs of integrated interaction torque components across subjects for slow (*black bars*), medium (*gray bars*), and fast throws (*open bars*). Torque components integrated over the same period as late interaction torque in Fig. 5G. *A* integrated late elbow extensor interaction torque (same as Fig. 5G). Parceled out torques were associated with parameters as follows: *B* shoulder deceleration (*Sa*); *C* wrist acceleration (*Wa*); *D* horizontal translational acceleration of the origin of the arm model (*Xa*); *E* vertical translational acceleration of the origin (*Ya*); *F* centripetal effects from shoulder angular velocity (*SS*); *G* centripetal effects from wrist angular velocity (*WW*); *H* Coriolis effects associated with shoulder and wrist angular velocities (*SW*); *I* Coriolis effects from elbow and wrist angular velocities (*EW*). *Bidirectional vertical arrow* indicates direction of torque at elbow joint. $^*P < 0.05$ (post hoc Tukey test)

the last 50 ms before ball release that an increase in the magnitude of the shoulder flexor interaction torque, coupled with a decrease in the magnitude of the shoulder extensor muscle torque, resulted in the late shoulder flexor net torque.

This finding occurred across subjects. This was demonstrated by integrating shoulder net torque, muscle torque, interaction torque, and gravity torque. Only those points were taken which occurred in the last 50 ms before ball release (Fig. 7a), and when net torque was in the flexor direction. Statistical analysis revealed that the late shoulder flexor net torque (Fig. 8A) was larger in magnitude for fast throws compared to slow and medium-speed throws [$F(1,12) = 19.9$, $P < 0.001$]. The increase in the late shoulder flexor net torque (Fig. 8A) was accounted for by shoulder flexor interaction torque (Fig. 8C), which was found to increase with each increase in throwing speed [$F(2,22) = 84.6$, $P < 0.001$]. The shoulder muscle torque (Fig. 8B) and the torque due to gravity (Fig. 8D) did not reliably change with throwing speed and were in the direction of shoulder extension.

In summary, late shoulder net torque in the flexion direction before ball release, which produced shoulder deceleration, was not caused by a shoulder flexor muscle torque. Rather, shoulder deceleration was produced by a shoulder flexor interaction torque.

Parceling out shoulder interaction torque

To determine the factors that contributed to the late shoulder flexor interaction torque, we parceled out its individual components. Each individual component was extracted from the total interaction torque for each trial of each subject and integrated over the same 50-ms time period that was used for integration of the late shoulder interaction torque (Fig. 8C). The integrated shoulder interaction torque components, averaged across subjects, are shown in Fig. 9 for the slow, medium, and fast throws. The integrated shoulder interaction torque values (the same values shown in Fig. 8C) are shown in Fig. 9A. The largest contribution to the late shoulder flexor interaction torque came from the effects of elbow extension angular acceleration (Fig. 9B) and from the centripetal effects of elbow extension angular velocity (Fig. 9F), both of which were in the shoulder flexion direction. The magnitude of the interaction torque component associated with elbow extension angular acceleration (Fig. 9B) increased with each increase in throwing speed [$F(1,13) = 79.4$, $P < 0.001$]. The magnitude of the component associated with the centripetal effects of elbow extension angular velocity (Fig. 9F) was greater for medium and fast speeds than for the slow speeds [$F(2,22) = 13.1$, $P < 0.001$]. In contrast, the component associated with wrist acceleration (Fig. 9C) was small and was significantly smaller in magnitude for fast throws when compared to slow throws [$F(1,15) = 6.8$, $P = 0.014$], presumably because over this period, wrist acceleration was decreasing in fast throws. There was very little change in the interaction torque components associated with the linear acceleration of the origin of the arm (Fig. 9D, E) and the centripetal effects of wrist angular velocity (Fig. 9G), and only small effects in the components associated with Coriolis effects (Fig. 9H–J).

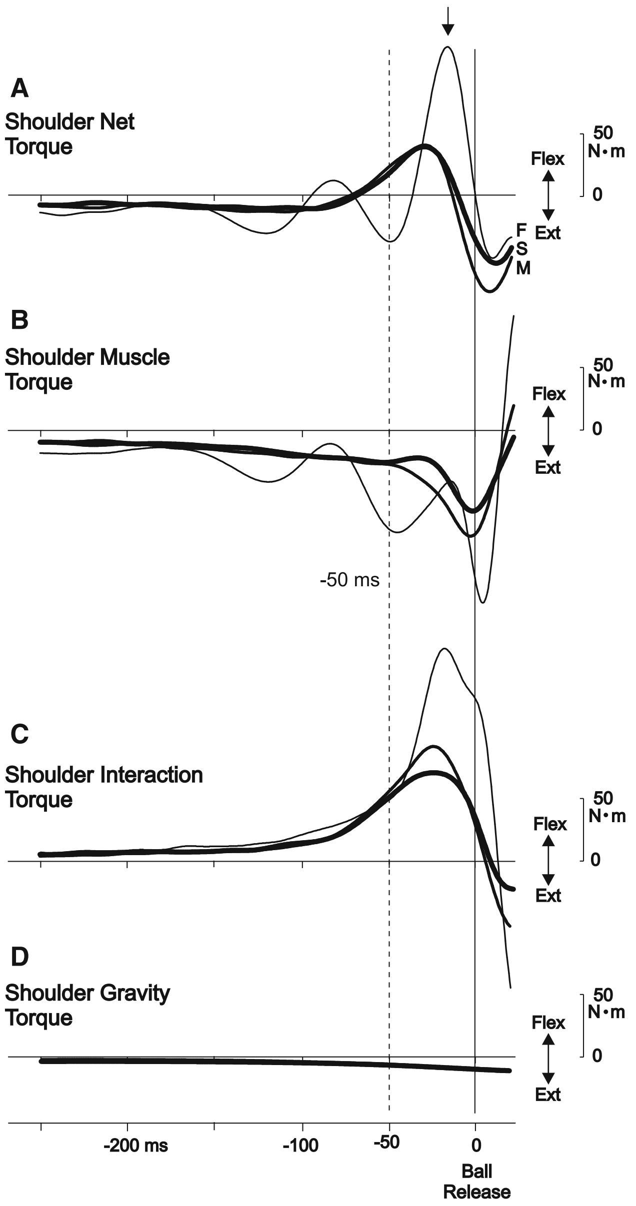

Fig. 7 Computed shoulder joint torques from representative subject (Pc). Each *trace* represents average of 20 throws for slow (*thick traces*), medium (*medium traces*), and fast throws (*thin traces*), aligned on time of ball release (*solid vertical line*, 0 ms). *Downward vertical arrow* indicates late-occurring shoulder flexor net torque. *Bidirectional vertical arrows* indicate direction of torque

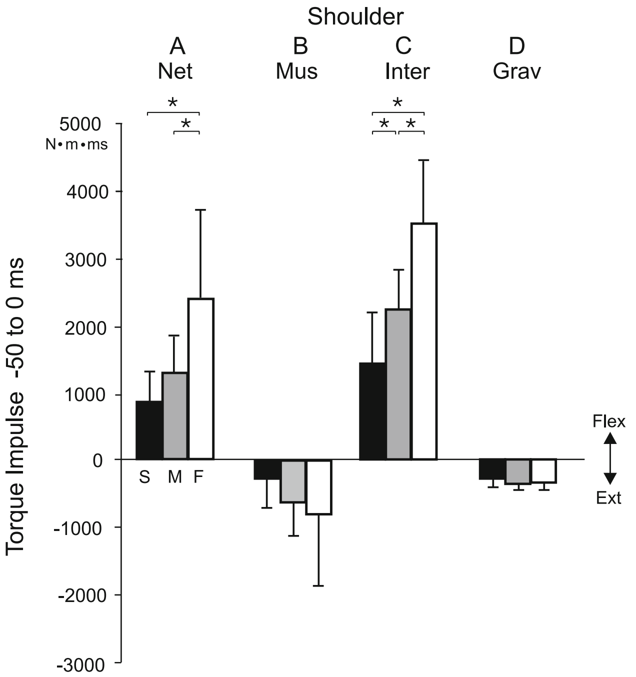

Fig. 8 Means and SDs of integrated shoulder torques across subjects for slow (*black bars*), medium (*gray bars*), and fast throws (*open bars*). *A–D* shoulder late flexor torque. Torque components were integrated over last 50 ms to ball release when net torque was in direction of shoulder flexion. *Bidirectional vertical arrows* indicate direction of torque. $*P < 0.05$ (post hoc Tukey test)

In summary, shoulder extension angular deceleration before ball release was produced by a late shoulder flexor interaction torque that primarily resulted from elbow extension acceleration and elbow extension velocity.

Overlap of proximal-to-distal and distal-to-proximal interaction torques

The results show that for fast throws, shoulder deceleration before ball release is caused by a distal-to-proximal interaction torque arising from elbow motion and that elbow motion is influenced by a late proximal-to-distal interaction torque arising from shoulder deceleration. To gain insight into the relationship between the shoulder and elbow interaction torques, we compared the timing of their duration over the final 50 ms before ball release for fast throws across subjects. For 10 of 12 subjects, a distal-to-proximal interaction torque at the shoulder in the flexion direction occurred over the entire 50 ms prior to ball release (cf. Fig. 7c). In contrast, the proximal-to-distal interaction torque at the elbow occurred over a shorter period of time. The onset of the late elbow extensor interaction torque occurred on average 31.9 ms (SD 10.8) prior to ball release (cf. Fig. 4c). For 5 of 12 subjects, including subject Pc (Fig. 4c), the interaction torque reversed direction to become a flexor interaction torque on average 5.6 ms (SD 3.6) prior to ball release (5 ms for subject Pc). For the remaining 7 of 12 subjects, the elbow extensor interaction torque continued past ball release. Thus, over the final 50 ms prior to ball release, there was a mean temporal overlap of shoulder and elbow interaction torques for 28.8 ms (SD 11.0). In summary, the passive dynamic effects arising from and influencing shoulder and elbow motion were related in time, i.e., in fast throws, for a period of approximately 30 ms prior to ball release, proximal-to-distal and distal-to-proximal

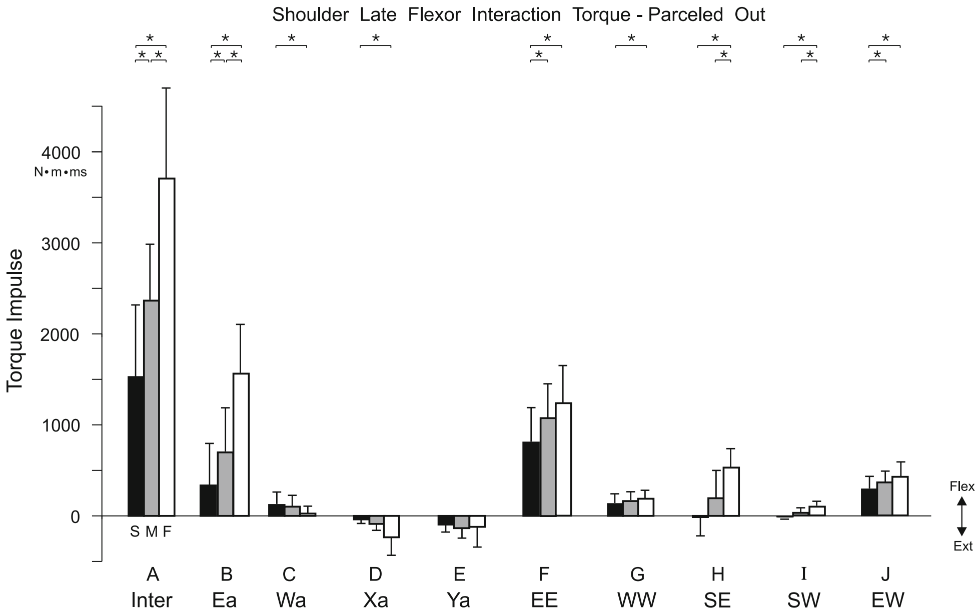

Fig. 9 Parceled out shoulder late flexor interaction torque. *Bars* represent the means and SDs of integrated interaction torque components across subjects for slow (*black bars*), medium (*gray bars*), and fast throws (*open bars*). Torque components integrated over same period as shoulder late interaction torque in Fig. 8C. *A* integrated interaction torque (same as Fig. 8C). Parceled out torques were associated as follows: *B* elbow acceleration (*Ea*); *C* wrist acceleration (*Wa*); *D* horizontal translational acceleration of the origin of the arm model (*Xa*); *E* vertical translational acceleration of the origin (*Ya*); *F* centripetal effects from elbow angular velocity (*EE*); *G* centripetal effects from wrist angular velocity (*WW*); *H* Coriolis effects from shoulder and elbow angular velocities (*SE*); *I* Coriolis effects from shoulder and wrist angular velocities (*SW*); *J* Coriolis effects from elbow and wrist angular velocities (EW). *Bidirectional vertical arrow* indicates direction of torque at shoulder joint. *$P < 0.05$ (post hoc Tukey test)

interaction torques between the shoulder and elbow occurred simultaneously.

Discussion

Origin of the shoulder and elbow interaction torques

Previous simulation studies of 2-D throwing suggested that the optimal strategy for generating distal joint speed involves an active torque reversal at the proximal joint through the generation of antagonist muscle activity (Herring and Chapman 1992; Chowdhary and Challis 2001). However, this was not the case for throws in the present study because, prior to ball release, shoulder muscle torque was always in the direction of shoulder extension (Figs. 7b, 8B), i.e., there was no evidence for antagonist shoulder flexor muscle torque. Instead, shoulder deceleration was produced by interaction torques associated with extension of the elbow. This finding that there was a large distal-to-proximal interaction torque that caused shoulder extension deceleration before ball release is consistent with the findings of Hirashima et al. (2003). Moreover, this result for the arm is similar to the mechanism used to decelerate the proximal joint in kicking motions of the leg (Putnam 1993; Sorensen et al. 1996).

The shoulder deceleration prior to ball release in fast throws generated a late-occurring interaction torque at the elbow in the extension direction (Fig. 4c, 5G). The majority of the interaction torque at the elbow was due to shoulder deceleration (Fig. 6B). This was an unexpected result since previous work suggested that a velocity-dependent interaction torque associated with the centripetal effect of shoulder angular velocity provided a significant contribution to the elbow extensor torque (Putnam 1993; Hirashima et al. 2003). Presumably, for the present results, the centripetal effects of shoulder motion were small because the shoulder angular velocity was decreasing late in the throw just before ball release (Fig. 2b). This late-occurring elbow extensor interaction torque contributed to increasing elbow extension acceleration and velocity. Although the majority of the elbow extensor net torque prior to ball release was due to elbow extensor muscle torque, the late elbow extensor interaction torque in fast throws contributed about 50% of the additional total extensor torque when going from medium to fast speeds.

Mechanical positive feedback of interaction torques

The relationship between shoulder extension deceleration and elbow extension acceleration in fast throws, before ball release, appears to be the consequence of a biomechanical property of the limb at high movement velocities. Given the finding that shoulder and elbow interaction torques occurred simultaneously for approximately 30 ms before ball release, we propose that in fast throws, distal-to-proximal and proximal-to-distal interaction torques entered into a system of mechanical positive feedback. This mechanical positive feedback mechanism should be interpreted as resulting from Newton's third law of motion (for every action there is an equal and opposite reaction) rather than resulting from an alternating process of cause and effect. The results indicate that the mechanical positive feedback was initiated by extensor muscle torque at the elbow which provided the early elbow extension acceleration and velocity. A strong distal-to-proximal flexor interaction torque at the shoulder was then produced (Figs. 7c, 8C) which counteracted the shoulder extensor muscle torque. The mechanical positive feedback of interaction torques presumably began when shoulder deceleration occurred, and proximal-to-distal interaction torques were generated at the elbow, which resulted in the sustained acceleration at the elbow. In this way, the elbow extensor muscles provided the energy for both the initial elbow acceleration and in part for the late elbow acceleration which occurred via the mechanical feedback mechanism.

In other multijoint tasks, interaction torques also only played a prominent role in fast movements. For example, in fast two-joint arm movements, large interaction torques dominated at the distal joint which resulted in a pattern of movement at the distal joint that resembled that produced by passively moving the proximal joint (Dounskaia et al. 1998, 2000). These authors suggested that at fast movement speeds, distal muscle torque was unable to compensate for large interaction torque. In many cases, the inability to compensate for passive limb dynamics results in movement inaccuracies. However, in the fast 2-D overarm throws, the passive deceleration at the shoulder, and the resulting interaction torque at the elbow, was advantageous.

CNS control of throwing

In recent studies of 2-D and 3-D skilled overarm baseball throwing, Hirashima et al. (2003, 2007) supported the idea that complex multijoint movements can be controlled by the nervous system using a hierarchical control strategy such as described by the Leading Joint Hypothesis (Dounskaia 2005). The Leading Joint Hypothesis proposes that planning of complex movement is simplified by choosing one "leading" joint, which provides the dynamic foundation for the entire movement. Kinematics of the leading joint are controlled actively with agonist–antagonist muscle activity similar to that used for the control of single joint movements. Adjacent "subordinate" joints are strongly influenced by passive dynamics, with subordinate muscle activity used to adjust joint kinematics to meet the requirements of the task. When we began this study, we thought that the shoulder joint, with large musculature and high inertia of the upper arm, would be the leading joint in 2-D throws. However, in some situations, it has been found that the elbow is the leading joint and the shoulder is the subordinate joint (cf. Dounskaia 2005; Galloway and Koshland 2002). The present evidence indicates that in fast 2-D throws, the elbow is the leading joint. For example, shoulder deceleration before ball release was not produced by active shoulder antagonist muscle torque. Instead, it was strongly influenced by interaction torques arising from elbow extension. Furthermore, elbow extension was primarily driven by elbow extensor muscle torque. Although there was an additional contribution of elbow extensor interaction torque near ball release from shoulder deceleration, this was due to a mechanism initiated by the active extension of the elbow.

It has become increasingly recognized that, in appropriate circumstances, the central nervous system exploits interaction torques to improve the efficiency of movement and to assist the desired motion of the distal joint (Bernstein 1967; Phillips et al. 1983; Schneider et al. 1989; Feltner 1989; Putnam 1991, 1993; Virji-Babul and Cooke 1995; Dounskaia et al. 1998, 2002; Goble et al. 2007). For throwing, interaction torques at the wrist were exploited in skilled standing 3-D throws (Debicki et al. 2004; Hirashima et al. 2007) but not in 2-D throws (Hirashima et al. 2003). At the elbow, interaction torques were used to generate fast elbow speeds in 2-D throws (Hirashima et al. 2003) and 3-D throws (Hirashima et al. 2007). The present results complement these findings by demonstrating that interaction torques can be exploited by facilitation of a mechanical positive feedback mechanism.

One last issue is the extent to which the subjects in our study, who were skilled at 3-D throwing, transferred skill to the seated 2-D situation. One possibility is that their general athletic ability enabled them to generate fast elbow extension motions which, in turn, generated the late shoulder flexor interaction torque. In this case, the ability to throw fast in 2-D was simply the fortuitous consequence of the fast elbow motion producing a large shoulder interaction torque. This is unlikely given that they threw fast and accurately in the first few throws. Rather, we favor the idea that the relatively large elbow extension velocities (Fig. 3b) and elbow extension muscle torques (Fig. 5F) were a strategy, learned through previous experience, of maximizing interaction torques at the shoulder and allowing the mechanical positive feedback mechanism to operate. The CNS facilitated (coordinated) this mechanism by not generating any antagonist muscle torque at the elbow, or shoulder, before ball release. This is an interesting result because in normal 3-D throws made by skilled subjects, braking of elbow extension occurs before ball release (Hore et al. 2005; Gray et al. 2006). Consequently, there must be different central strategies for the control of interaction torque at the elbow in skilled 2-D and 3-D throws. Nevertheless, the mechanical positive feedback mechanism could occur early in the 3-D throws. Given the well-known role of the cerebellum in the control of interaction torques (e.g., Bastian et al. 1996, 2000), we have proposed that the inability of patients with cerebellar lesions and unskilled subjects to throw fast results from their failure to exploit interaction torques (Timmann et al. 2008). We now propose for future work that this could involve a failure to facilitate the mechanical positive feedback mechanism.

Conclusion

It is concluded that in the generation of fast 2-D throws, the CNS utilized the biomechanical properties of the arm to increase ball speed. It did this by coordinating motion at shoulder and elbow such that a simultaneous mechanical positive feedback occurred of interaction torques at elbow and shoulder. This, in turn, resulted in a late increase in elbow acceleration and velocity before ball release. To what extent this mechanical positive feedback mechanism is utilized by the CNS in other fast-skilled multijoint arm movements remains to be determined.

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