Utilization and compensation of interaction torques during ball-throwing movements

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1 Abstract

The manner in which the CNS deals with interaction torques at each joint in ball throwing was investigated by instructing subjects to throw a ball at three different speeds, using two (elbow and wrist) or three joints (shoulder, elbow, and wrist). The results indicated that the role of the muscle torque at the most proximal joint was to accelerate the most proximal joint and to produce the effect of interjoint interaction on the distal joints. In the three-joint throwing, shoulder muscle torque produced the assistive interaction torque for the elbow, which was effectively utilized to generate large elbow angular velocity when throwing fast. However, at the wrist, the muscle torque always counteracted the interaction torque. By this kinetic mechanism, the wrist angular velocity at the ball-release time was kept relatively constant irrespective of ball speed, which would lead to an accurate ball release. Thus, it was concluded that humans can adjust the speed and accuracy of ball-throwing by utilizing interaction torque or compensating for it.
2 Introduction

Most human and animal movements include the rotations of two or more joints. In multijoint limb movements, torque at one joint occurs not only from muscles acting at that joint but also from interactions due to the rotations of other joints (Hollerbach and Flash 1982). The net torque around one joint, which is proportional to the angular acceleration at the joint, is represented as the sum of the muscle torque, gravity torque, and interaction torque. Therefore, the central nervous system (CNS) is required to generate appropriate motor commands taking all these torques into consideration in order to execute the desired multijoint movement. The interaction torque is one of the self-generated load that is generated by the movement itself and is absent before the motion. Recent studies have demonstrated the ability of humans to predict and compensate for the self-generated loads such as the Coriolis force (Cohn et al. 2000; DiZio and Lackner 1995, 2000, 2001; Lackner and DiZio 1994), the tangential load force in lifting or transporting the object (Flanagan and Wing 1993, 1995, 1997; Johansson et al. 1992a, 1992b; Johansson and Westling 1984, 1988), the back force from the ball in throwing (Hore et al. 1999, 2001), and the interaction torque in multijoint movements (Almeida et al. 2000; Beer et al. 2000; Grible and Ostry 1999; Koshland et al. 2000; Sainburg et al. 1993, 1995, 1999, 2000, 2002; Topka et al. 1998). Studies on patients with nervous system injury clearly indicated that the compensation for the interaction torque is essential for the execution of the accurate multijoint movements. In reaching movement, for example, cerebellar patients could not deal with the interaction torque appropriately, and, as a consequence, an abnormally curved hand path was produced (Bastian et al. 1996).
Ball-throwing is one of the most skilled multijoint movements requiring excellent coordination between joints. Humans can throw a ball with wide range of ball speed keeping hitting accuracy. To accomplish this, the CNS must produce the appropriate motor command predicting the back forces from the ball and the interaction torque at each joint. Hore et al. (2001) examined skilled throwers’ ability to predict the back forces by instructing them to throw balls of different weights and diameters with different speeds. The skilled throwers could adjust the finger grip force in proportion to the back forces and could keep the amplitude of finger extension relatively constant from throw to throw. In addition, Timmann et al. (2001) showed that cerebellar patients and unskilled throwers could not control the finger grip force or finger extension precisely. These findings show that the CNS of the skilled ball-thrower could predict and compensate for the back force that is caused by the hand acceleration.

This hand acceleration is generated by the proximal-to-distal sequence of joint rotations (Putnam 1993) that is produced by the proximal-to-distal sequential muscle activities (Hirashima et al. 2002). However it is unclear how the CNS deals with the interaction torque at each joint during throwing. The purpose of this study is to examine the general feature of the interaction torque that is determined by the mechanics or the trajectories of the arm in throwing, and to determine how the CNS makes use of or compensates for the interaction torque at each joint in order to throw a ball with the desired speed and accuracy. We examine the intersegmental dynamics in the upper extremity by instructing subjects to throw a ball with different speeds (slow, medium and fast) in random order. Because the intersegmental dynamics is greatly influenced by the joint angular velocity and angular accelera-
tion (Hollerbach and Flash 1982), in order to throw a ball with desired speed it is essential for the CNS to precisely predict and compensate for the interaction torque at each joint from throw to throw. In addition, since the number of joints mobilized in throwing affects the intersegmental dynamics, we compare the two-joint throwing (elbow and wrist) with three-joint throwing (shoulder, elbow and wrist). Thus, we are able to investigate general feature of the intersegmental dynamics of throwing and its changes caused by the differences of the ball speed and the number of mobilized joints. We also discuss the strategy the CNS would use in order to adjust the ball speed and to release the ball accurately.

3 Methods

3.1 Subjects

Eight healthy right-handed males (mean age: 23.8 years) volunteered as subjects in this study. Subjects were clearly informed of the procedures of the experiment, according to the Declaration of Helsinki and gave a written informed consent before the experiment. This experimental procedure was approved by the Ethical Committee of the Graduate School of Arts and Sciences of the University of Tokyo. The subjects had no musculoskeletal disorders and were in excellent physical condition. There were two baseball players among the subjects (subjects A and B). However, they were not treated separately, since their feature of the intersegmental dynamics was similar to that of the other subjects, and it was not the purpose of this study to identify the difference between skilled and unskilled throwing.
3.2 Apparatus, and protocols

This study examined two types of throwing: 1) “two-joint throwing,” which includes elbow and wrist joint rotations (eight subjects), and 2) “three-joint throwing,” which includes shoulder, elbow and wrist joint rotations (seven subjects). Reflective markers were attached to the shoulder, elbow, wrist, and metacarpophalangeal (MP) joints of the right side of the right arm. During two-joint throwing, subjects were instructed to throw without translation of the elbow. During three-joint throwing, subjects were instructed to throw, as much as possible, without translation of the shoulder. Since actually there were some translations, we took the translation into consideration in calculating the inverse dynamics (see Appendix).

We instructed subjects to throw a straight ball with all markers in one vertical plane throughout the movement without pronation or supination of the forearm and not to throw a curve ball. Some subjects started with two-joint throwing; the others started with three-joint throwing. Throws were made under three different speed conditions: 1) “slow-accurate,” 2) “medium-accurate,” and 3) “fast-accurate.” Each of three conditions was randomly presented once to construct one bout. Ten bouts were repeated. Thus, in each condition, subjects made 10 throws. Each subject made a total of 60 throws (30 for two-joint and 30 for three-joint). Additional care was taken so that the same condition was not repeated consecutively, in order to force subjects to predict and compensate for the interaction torque from throw to throw stronger than in the case of repeating same speed. After a warm-up, subjects threw a baseball using the right hand toward a target on a wall (Fig. 1). The subjects were instructed to put the arm prior to the throw in the initial position in which the passive torque from the connective tissues of the arm balanced with gravity torque
(Fig. 1). The horizontal distance between the wall and the elbow joint in two-joint throwing was 2.7 m (Fig. 1A). The horizontal distance between the wall and the shoulder joint in three-joint throwing was 3.2 m (Fig. 1B). The height of the center of the target was 0.2 m above the height of the eye. The target board was a $1 \times 1$ m square. When the ball did not hit the target board, the trial was repeated.

### 3.3 Kinematic analysis

Motions of the markers were recorded at 200 Hz using two high-speed video cameras (HAS-200R, Ditect). By using the Direct Linear Transformation (DLT) method, time-position data in three dimensions were obtained. We considered the projections of markers to the plane that is determined by the three points (shoulder, elbow and wrist) when the elbow joint angle was right angle. Angular displacements at each joint were obtained in this plane. Joint angles are shown in Fig. 1. We did not adopt “segment angles” (Hoy et al. 1985) but instead adopted the conventional “joint angles” of Hollerbach and Flash (1982). Cooper et al. (2000) and Sainburg et al. (1995) recommended “joint angles” because the nervous system has proprioceptive information about the joint motion but lacks a direct measure of “segment angles.” Therefore, the equations of motion in terms of “joint angles” would more accurately represent the control problem from the viewpoint of the brain.

The direction of the arrow in the stick pictures in Fig. 1 represents the positive direction of the angular displacement. For example, the positive direction of the $\theta_1$ represents the elbow flexion during two-joint throwing. Note that the throwing motion consists of the elbow extension (negative direction) and wrist flexion (negative direction) for two-joint throwing (Fig. 2B), and the shoulder extension (negative direction), elbow extension (negative direction) and wrist flexion (negative direction)
Angular displacement data were smoothed with the use of the bidirectional fourth-order Butterworth low-pass filter (cut-off frequency = 13 Hz) and were numerically differentiated to obtain angular velocity and angular acceleration. The onset of the movement was detected as the time when the angular velocity at the most proximal joint exceeded 10% of its maximum.

### 3.4 Kinetic analysis

We employed inverse dynamics and calculated the time series of 1) the net torque (NET), 2) the gravity torque (GRA), 3) the interaction torque (INT), and 4) the muscle torque (MUS) about the shoulder, elbow, and wrist joints. Complete mathematical equations are presented in the Appendix. Anthropometric data are based on the data of Japanese athletes by Ae et al. (1992), which appears on the paper by Yokoi et al. (1998). With respect to these four torques, clear definitions and in-depth explanations have been given in several studies (Bastian et al. 1996, 2000; Cooper et al. 2000; Hollerbach and Flash 1982).

1) Bastian et al. (1996) calculated the NET as the product of the moment of inertia of the involved segments (including the segment under consideration and all segments distal to it) and the angular acceleration around the joint under consideration. We adopted this definition. As the NET is defined as the sum of other components, it is described as follows:

\[
\text{NET} = \text{GRA} + \text{INT} + \text{MUS}.
\]

2) The GRA is the term with the gravitational acceleration.

3) The INT at each joint is the sum of the terms with the angular accelerations of the other joint (inertial torque), the terms with the product of the angular velocities of the
same joint (centripetal torque), the terms with the product of the angular velocities of the different joints (Coriolis torque), and the terms with the linear acceleration of the most proximal joint (see Hollerbach and Flash 1982).

4) As the MUS is calculated as residual terms as follows:

\[ \text{MUS} = \text{NET-GRA-INT}, \]

the MUS is sometimes called “residual torque”. It is noted that the MUS includes not only the mechanical contribution of muscle contraction acting at the joint but also the passive contributions by muscles, tendons, ligaments, articular capsules, and other connective tissues.

3.5 Index of coordination between the interaction torque and the muscle torque (IOCIM)

There are two representative coordination relationships between the interaction torque and the muscle torque. One is the “counteractive” relationship, which is always seen at the wrist joint during reaching movements (Dounskaia et al. 1998; Galloway and Koshland 2002; Ghez et al. 1996; Koshland et al. 2000; Virji-Babul and Cooke 1995). In counteractive relationship, the muscle torque plays a counteractive role against the interaction torque and keeps the net torque relatively small throughout the movement. The counteractive relationship is also seen during the single-joint instructed movements (Almeida et al. 1995; Bastian et al. 2000; Galloway and Koshland 2002; Gribble and Ostry 1999) in which subjects were instructed to move only one joint (focal joint) without moving other joints (nonfocal joints). Subjects kept the nonfocal joints motionless during the motion of the focal joint by the muscle torque appropriately counteracting the interaction torque at the nonfocal joints. The other is the “assistive” relationship, which is sometimes seen at
the elbow joint during reaching movements (Galloway and Koshland 2002). In the assistive relationship, the muscle torque and the interaction torque work together for the same direction to generate larger net torque. This assistive relationship is advantageous for generating large angular velocity at the joint.

In order to quantify intersegmental dynamics, we made the index of coordination between the interaction torque and the muscle torque (IOCIM) so that this index can distinguish the “counteractive” or “assistive” relationship. IOCIM for one trial was calculated as follows:

\[
\text{IOCIM} = \frac{\int_{T_1}^{T_2} I(t)dt}{\int_{T_1}^{T_2} M(t)dt}
\]

where \(T_1\) is the time of movement onset at the most proximal joint and \(T_2\) is the ball-release time, \(I(t)\) and \(M(t)\) was calculated as follows:

\[
I(t) = \begin{cases} 
-|\text{INT}(t)| & (\text{INT}(t) \cdot \text{MUS}(t) < 0) \\
+|\text{INT}(t)| & (\text{INT}(t) \cdot \text{MUS}(t) \geq 0)
\end{cases}
\]

\[
M(t) = +|\text{MUS}(t)|
\]

The positive sign of IOCIM indicates the “assistive” relationship, and the negative sign of IOCIM indicates the “counteractive” relationship from \(T_1\) to \(T_2\) as a whole. The magnitude of the IOCIM indicated the relative magnitude of the interaction torque to the muscle torque. For example, IOCIM value of +1.0 occurs when the interaction torque and the muscle torque have the same direction and the same amount
of torque impulse; -1.0 occurs when they have the opposite direction and the same amount of torque impulse; -0.5 occurs when they have the opposite direction and the interaction torque impulse is half of the muscle torque impulse.

### 3.6 Statistics

A repeated-measures ANOVA was performed to assess the effect of the speed on the MUS impulse, INT impulse, NET impulse, and angular velocity at the ball-release time ($P < 0.05$). Tukey’s post-hoc multiple comparison tests determined the increase or decrease of these variables between speeds ($P < 0.05$).

### 4 Results

The results consist of two main sections. The first section shows the general features of the kinematics and kinetics in throwing movements, especially focusing on the relationship between the interaction torque and muscle torque. These features are necessary to understand the mechanisms of the strategy to adjust the ball speed that is clarified in the second section. Each section consists of two subsections, i.e., two-joint throwing and three-joint throwing.

#### 4.1 General features of the kinematics and kinetics in throwing movements

##### 4.1.1 Two-joint throwing

Figure 2A shows stick pictures of one trial for subject A, when throwing balls at three different speeds (slow, medium and fast) with two joints. Figures 2B and 2C show the kinematics of the same trials of Fig. 2A. Figure 2D shows the kinetics of them. The ball-release time was set to 0 ms. First the elbow started to extend (Slow, -235 ms; Medium, -195 ms; Fast, -160 ms; see Fig. 2C). Next the wrist started to
Elbow For all speeds, before the movements, the elbow extension muscle torque was kept at a magnitude that opposed the flexion gravity torque and it held the elbow in the starting position (Fig. 2D). Next, from about -200 ms to -100 ms, the subject increased the elbow extension muscle torque to produce the elbow extension net torque that is proportional to the angular acceleration of the elbow. This elbow extension net torque initiated the two-joint throwing (Fig. 2C). In this initial phase, the elbow interaction torque had little effect at the elbow. Next, from about -100 ms to 0 ms, the elbow flexion interaction torque occurred and counteracted the elbow muscle torque almost throughout this phase.

In order to clearly determine whether there was the counteractive or assistive relationship, the interaction torque was plotted against the muscle torque from the movement onset to the ball-release time for the same trial of Fig. 2 (see Fig. 3A). In the elbow joint in Fig. 3A, most of the plots exist in the second quadrant. This means that the interaction torque and the muscle torque always showed different signs, i.e., the "counteractive" relationship. The IOCIM (index of coordination between INT and MUS, see Method) is also shown in Fig. 3A. All IOCIMs for the elbow showed negative sign (i.e., the "counteractive" relationship). Figure 3B shows the interaction torques of all trials for all subjects plotted against their muscle torques for two-joint throwing. Averages of IOCIM across all subjects are also shown. They all show negative sign.

Wrist For all speeds, before the movements, the wrist flexion muscle torque was kept at a magnitude that opposed the extension gravity torque and it held the wrist flex (about -80 ms), and the ball was released (0 ms).
in the starting position (Fig. 2D). After the start of the movement, the wrist muscle torque mirrored and counteracted the interaction torque throughout the movement. It should be noted that the wrist flexion muscle torque was appropriately scaled to counteract the large wrist extension interaction torque in the fast condition.

The wrist interaction torque was also plotted in Fig. 3A against the wrist muscle torque from the movement onset to the ball-release time for the same trial of Fig. 2. In Figs. 3A and 3B, at the wrist, diagonal straight lines are present in all conditions. A diagonal straight line indicates that the interaction torque and the muscle torque are approximately mirror images of each other (Bastian et al. 1996). All IOCIMs in Figs. 3A and 3B for the wrist showed negative sign (i.e., the “counteractive” relationship).

### 4.1.2 Three-joint throwing

Figure 4A shows stick pictures of one trial for subject A, when throwing balls at three different speeds (slow, medium, and fast) with three joints. Figures 4B and 4C show the kinematics of the same trials of Fig. 4A. Figure 4D shows the kinetics of them. The ball-release time was set to 0 ms. At first the shoulder started to extend (Slow, -360 ms; Medium, -265 ms; Fast, -260 ms; see Fig. 4C). Next the elbow started to extend. Finally the wrist started to flex, and the ball was released (0 ms).

**Shoulder** The kinetic feature of the shoulder during three-joint throwing was similar to that of the elbow during two-joint throwing. There was an initial phase in which the effect of the interaction torque was little. In the fast condition, for example, the initial phase was from about -250 ms to about -100 ms. In this phase, the subject increased the shoulder extension muscle torque to produce the shoulder
extension net torque, which initiated the three-joint throwing (Figs. 4C and 4D). Next the shoulder flexion interaction torque had very large effect on the shoulder net torque; as a consequence, the shoulder extension net torque was changed to the shoulder flexion net torque (Fig. 4D).

The shoulder interaction torque was plotted in Fig. 5A against the shoulder muscle torque from the movement onset to the ball-release time for the same trial of Fig. 4. In the shoulder joint in Fig. 5A, most of the plots exist in the second quadrant. This means that the interaction torque and the muscle torque always showed different signs, i.e., the “counteractive” relationship. All IOCIMs for the shoulder show negative sign (i.e., the “counteractive” relationship). Figure 5B shows the interaction torques of all the trials for all the subjects plotted against their muscle torques for three-joint throwing. Averages of IOCIM across all the subjects are also shown. They all show negative sign at the shoulder (i.e., the “counteractive” relationship).

**Elbow** The kinetic feature of the elbow during three-joint throwing was clearly different from that of the elbow during two-joint throwing. The elbow extension interaction torque assisted the elbow extension muscle torque for all conditions, though in the slow and medium condition the assistive interaction torque is small throughout the throwing (Fig. 4D). It should be noted that, in the fast condition, large elbow extension net torque was generated by the large extension interaction torque assisting the extension muscle torque (Fig. 4D), and as a consequence, large elbow angular velocity for extension occurred (Fig. 4C). Figures 5A and 5B show that most of the plots for the elbow are in the third quadrant and that all IOCIM values show positive signs (i.e., the “assistive” relationship), though in the slow condition the IOCIM is almost zero.
**Wrist**  The kinetic feature of the wrist during three-joint throwing was very similar to that of the wrist during two-joint throwing. The wrist muscle torque mirrored and counteracted the interaction torque to allow a controlled wrist flexion (Fig. 4D). In Figures 5A and 5B diagonal straight lines were clear for all conditions at the wrist. All IOCIM values showed negative signs (i.e., the “counteractive” relationship).

### 4.1.3 Summary

The general features of intersegmental dynamics for the planar throwing movements can be summarized as follows:

1. **At the proximal joint of the most proximal segment** (i.e., the elbow joint in two-joint throwing and the shoulder joint in three-joint throwing), there was an initial phase in which the effect of the interaction torque was little, in other words the change of the net torque was mainly determined by the change of the muscle torque. This net torque initiated the throwing motion. Next, the interaction torque occurred for the opposite direction to the muscle torque.

2. **At the wrist joint**, the “counteractive” relationship between muscle torque and interaction torque was always observed. Interestingly, the larger wrist flexion muscle torque counteracted the larger wrist extension interaction torque.

3. **The difference of the intersegmental dynamics**, which was caused by the number of the mobilized joints, was seen at the elbow especially in the fast condition. In three-joint throwing, the elbow extension interaction torque assisted the elbow extension muscle torque to generate the large elbow extension net torque. This “assistive” relationship contributed to generating very large angular velocity at the elbow for the fast condition.
4.2 **Strategy to adjust the ball speed**

The intersegmental dynamics is greatly influenced by the joint angular velocity and angular acceleration (Hollerbach and Flash 1982). Therefore, throwers must generate an appropriate motor command by anticipating the complex and time-varying interaction torque caused by the throwing motion itself with the desired speed. It is totally unknown how the CNS deals with the interaction torque when adjusting the movement speed in ball-throwing movements. Is there any effective strategy to ensure the accuracy of the performance when adjusting the ball speed from throw to throw?

At first, it was examined whether subjects could throw balls with three different speeds. A repeated-measures ANOVA revealed a significant main effect of speed specification (two-joint throwing: $F(2,14) = 83.0$, three-joint throwing: $F(2,12) = 73.6$) on the actual ball speed. Tukey’s post-hoc multiple comparison tests indicated significant differences for all comparisons between slow (5.46±0.30 m/s), medium (6.49±0.41 m/s), and fast (8.02±0.51 m/s) conditions in two-joint throwing ($Ps < 0.05$) and for all comparisons between slow (6.07±0.32 m/s), medium (8.27±0.54 m/s), and fast (11.4±1.33 m/s) conditions in three-joint throwing ($Ps < 0.05$). Subjects could throw the balls using three different speeds. In addition, it was examined whether angular velocity for each joint at the ball-release time changed with the three speed conditions.

4.2.1 **Two-joint throwing**

The angular velocity at the ball-release time during two-joint throwing, which was averaged across all subjects, is shown in the rightmost column of Fig. 6. A repeated-measures ANOVA was performed to assess the effect of speed on angular
velocity at the ball-release time at the elbow and wrist joints. It revealed a significant main effect of speed at the elbow ($F(2,14) = 82.6$). However, interestingly, there was no significant main effect of speed at the wrist ($F(2,14) = 0.18; P > 0.8$). The results of Tukey’s post-hoc multiple comparison tests are shown in the rightmost column of Fig. 6. This indicates that the wrist angular velocity at the ball-release time was kept relatively constant in spite of the increase of ball speed and that only elbow angular velocity contributed to the increase of ball speed.

We examined the mechanism whereby the wrist angular velocity at the ball-release time was kept constant by calculating the muscle torque impulse (MUSIm), the interaction torque impulse (INTIm), and the net torque impulse (NETIm), which are calculated as follows:

\[
\text{MUSIm} = \int_{T_1}^{T_2} MUS(t)dt,
\]

\[
\text{INTIm} = \int_{T_1}^{T_2} INT(t)dt,
\]

\[
\text{NETIm} = \int_{T_1}^{T_2} NET(t)dt,
\]

where $T_1$ is the time of movement onset at the most proximal joint and $T_2$ is the ball-release time. MUSIm, INTIm, and NETIm, which were averaged across all subjects, are shown in Fig. 6. Repeated-measures ANOVAs were performed to assess the effect of speed on the MUSIm, INTIm, and NETIm at the elbow and wrist joints, revealing significant main effects of speed on the elbow MUSIm ($F(2,14) = 75.8$),
the elbow INTIm ($F(2,14) = 5.43$), the elbow NETIm ($F(2,14) = 54.4$), the wrist MUSIm ($F(2,14) = 67.7$), and the wrist INTIm ($F(2,14) = 39.3$) but no significant main effect of speed on the wrist NETIm ($F(2,14) = 2.85; P > 0.09$). The results of Tukey’s post-hoc multiple comparison tests on the MUSIm, INTIm, and NETIm in two-joint throwing are shown in Fig. 6.

Figure 6 shows that, although the elbow flexion INTIm increased a little with the ball speed, the increase of the elbow extension MUSIm overcame it to realize the increase of the elbow extension angular velocity with the ball speed. In contrast, the wrist extension INTIm also increased with the ball speed, and this increase of the wrist extension INTIm was exactly counteracted by the increase of the wrist flexion MUSIm; as a result, the wrist flexion angular velocity at the ball-release time was kept relatively constant irrespective of the ball speed. In addition, interestingly, a time-series of the wrist angular velocity between -80 ms and 0 ms was also kept relatively constant irrespective of the ball speed (see Fig. 2C).

### 4.2.2 Three-joint throwing

The same analysis was also performed for three-joint throwing. The angular velocity at the ball-release time during three-joint throwing, which was averaged across all subjects, is shown in the rightmost column of Fig. 7. A repeated-measures ANOVA was performed to assess the effect of speed on angular velocity at the ball-release time at the shoulder, elbow and wrist joints. It revealed significant main effects of speed at the shoulder ($F(2,12) = 21.8$) and at the elbow ($F(2,12) = 46.7$). However, interestingly, there was no significant main effect of speed at the wrist ($F(2,12) = 0.09; P > 0.9$) as well as for two-joint throwing. The results of Tukey’s post-hoc multiple comparison tests again testified that wrist angular velocity at the
ball-release time was kept relatively constant in spite of the increase of ball speed and that only the shoulder and elbow angular velocity contributed to the increase of ball speed.

Repeated-measures ANOVAs on the MUSIm, INTIm, and NETIm at the shoulder, elbow, and wrist joints revealed significant main effects of speed on the shoulder MUSIm ($F(2,12) = 90.0$), the shoulder INTIm ($F(2,12) = 42.7$), the shoulder NETIm ($F(2,12) = 4.26$), the elbow MUSIm ($F(2,12) = 12.3$), the elbow INTIm ($F(2,12) = 15.5$), the elbow NETIm ($F(2,12) = 40.7$), the wrist MUSIm ($F(2,12) = 14.1$) and the wrist INTIm ($F(2,12) = 23.3$) but no significant main effect of speed on the wrist NETIm ($F(2,12) = 0.17; P > 0.8$). The results of Tukey’s post-hoc multiple comparison tests are shown in Fig. 7.

Figure 7 indicates that the method for increasing the shoulder extension angular velocity at the ball release during three-joint throwing was the same as that for increasing the elbow extension angular velocity during two-joint throwing, i.e., the CNS increased the shoulder extension MUSIm that overcame the increase of the shoulder flexion INTIm.

At the elbow, the MUSIm’s contribution to the increase of the NETIm was not particularly large, as shown by the fact that there was no significant difference in the MUSIm between the slow and fast conditions. Alternatively, the INTIm in the fast condition was significantly larger than that in the slow condition. As the direction of the elbow INTIm in the three-joint throwing was extension (desired direction), the CNS could utilize this elbow extension INTIm to increase the elbow extension angular velocity at the ball-release time.

In the same way as in the two-joint throwing, the increase of the wrist extension
INTIm was exactly counteracted by the increase of the wrist flexion MUSIm in the three-joint throwing. Thus, the wrist flexion angular velocity at the ball-release time was kept relatively constant irrespective of the ball speed. In addition, the time series of the wrist angular velocity between -80 ms and 0 ms was also kept relatively constant irrespective of the ball speed (see Fig. 4C).

5 Discussion

Hierarchical control  The results showed that, at the most proximal joint (i.e., the elbow joint in two-joint throwing and the shoulder joint in three-joint throwing), the muscle torque counteracted the interaction torque as well as at the wrist joint, which is indicated by the fact that the IOCIM values showed negative signs. However, the role of the muscle torque at the most proximal joint is different from that at the wrist. At the most proximal joint, there was an initial phase in which the change of the muscle torque predominantly determined the change of the net torque. This initial net torque initiated the throwing motion. The role of the muscle torque in the initial phase was not counteracting the interaction torque but accelerating the most proximal segment. Furthermore, in the three-joint throwing, the role of the shoulder muscle torque in the initial phase was not only to accelerate the shoulder joint but also to produce the assistive interaction torque for the elbow.

Dounskaia et al. (1998) suggested a hierarchical control, in which the role of the proximal muscle is to generate movement of the whole linkage and the role of the distal muscle is to produce corrections of the movement necessary to fulfill the task. Bernstein (1967, 1996) insightfully suggested that the role of the muscle activity is not only to accelerate the limb but also to control the intersegmental interaction.
The results here support these ideas. In three-joint throwing, throwers effectively utilized assistive interaction torque and produced larger elbow angular velocity to satisfy the demand of the fast condition. It is also interesting that the CNS realized the increase of the elbow angular velocity depending mainly upon the increase of the assistive interaction torque impulse (INTIm) in three-joint throwing (Fig. 7) but upon the muscle torque impulse (MUSIm) in two-joint throwing (Fig. 6). The role of the elbow muscle torque in three-joint throwing was to assist the effects of intersegmental interaction, while the role of the elbow muscle torque in two-joint throwing was to accelerate the limb by itself.

**Assistive relationship between interaction and muscle torque** Putnam (1991, 1993) provided insights into the intersegmental dynamics in walking, ball kicking, and ball throwing. Putnam’s discussion was similar to hierarchical control theory, which suggests that the interaction torque produced by the shoulder motion was utilized at the elbow in ball throwing. In this study, the existence of the assistive relationship between interaction and muscle torque was confirmed at the elbow in three-joint throwing. However, the assistive relationship was not identified at the wrist. Interestingly, Koshland et al. (2000) reported that no case of reaching has been described in which the wrist muscle torque assisted the interaction torques at the wrist joint, giving several examples (Dounskaia et al. 1998; Ghez et al. 1996; Virji-Babul and Cooke 1995). It remains to be answered whether the counteractive relationship at the wrist is caused by the neural contribution or the musculoskeletal properties at the wrist or a combination of these two factors.
**Compensation for the interaction torque at the wrist** At the wrist joint, the muscle torque exactly counteracted the interaction torque during both two- and three-joint throwing. The mirror relationship between the interaction and muscle torque indicates that this compensation would be performed by the feedforward control. On-line feedback is not feasible. If compensation were performed by on-line feedback, a corrective motor command would no longer be appropriate for the current state of the limb due to the feedback delay, especially in a fast movement, such as ball throwing.

Sainburg et al. (1993, 1995) supposed that the deficit in interjoint coordination of the patients without proprioception was not attributed to deficits in on-line feedback. They hypothesized that proprioceptive information is used to update the internal model of the limb in the current environment. Ghez et al. (1990) and Godon et al. (1995) demonstrated that visual information of a limb movement could improve interjoint coordination of patients without proprioception. On the other hand, visual information could not improve the interjoint coordination of cerebellar patients (Beppu et al. 1987; Brown et al. 1993; van Donkelaar and Lee 1994). This indicates that the cerebellum is responsible for updating the internal model by using proprioceptive or visual information. By using an fMRI, Imamizu et al. (2000) showed that the cerebellum is involved in acquiring an internal model.

These findings are compatible with the studies about ball throwing by Hore and Timmann. Skilled throwers can predict the back force from the ball and compensate for it by producing appropriate finger grip force (Hore et al. 1999, 2001). On the other hand, cerebellar patients and unskilled subjects could not control finger grip force appropriately (Timmann et al. 2001). These findings indicate that poor
throwers have not acquired the appropriate internal model for throwing. Results of our present study further indicate that throwers can also predict and compensate for the interaction torque at the wrist.

However, it is noted that the muscle torque calculated by inverse dynamics includes not only the mechanical contribution of active muscle contraction at the joint but also passive contributions (passive torque) by muscles, tendons, ligaments, articular capsules, and other connective tissues. Therefore, the possibility that the compensation for the interaction torque was achieved by the passive torque at the wrist joint cannot be excluded. Furthermore, the passive torque appears with a feedback delay of 0 ms. As noted by Dounskaia et al. (1998), attention must be given to the passive torque, if the joint rotates around the extremity of the range of motion. Stiffness control is also feasible. Osu et al. (2002) hypothesized that viscoelasticity contributes more when an internal model is inaccurate, while internal models contribute more after the accurate internal model is acquired.

In order to determine whether this compensation is realized by the feedforward time-varying control or the stiffness control, the electromyographic (EMG) studies recording the agonists and antagonists at the wrist are necessary. If there were co-activation of agonists and antagonists, it would be likely that the CNS used the stiffness control. However, some recent studies revealed the reciprocal EMG pattern between the flexor (agonist) and extensor (antagonist) of the wrist during over-arm badminton smash stroke (Sakurai and Ohtsuki 2000) and baseball pitching (Hirashima et al. 2002), implying feedforward time-varying control. The computer simulation would be also useful to determine whether it is possible or not for the high stiffness at the wrist to realize this compensation. At the present stage, it ap-
pears that throwers can compensate for the interaction torque at the wrist by the neuromusculoskeletal system as a whole.

**The role of the wrist**  The role of the wrist in ball throwing is discussed here. The strategy used by the CNS was that the elbow and shoulder contributed to adjustments of ball speed but the wrist did not. As the length of the hand is shorter than that of the forearm and upper arm, the angular velocity of the wrist is less effective for increasing ball speed than the angular velocity of the elbow and shoulder. This may be one of the reasons why the wrist does not contribute to the adjustment of ball speed. However, a more feasible reason would be that the role of the wrist is to simplify the control of the finger grip force, leading to an accurate ball release. Since the extrinsic finger muscles cross the wrist joint, the wrist motion affects the length and velocity of the extrinsic finger muscles and finally affects the force-producing capacity of the extrinsic finger muscles (Brand 1985; Herrmann and Delp 1999; O’Driscoll et al. 1992). Werremeyer and Cole (1997) showed that the wrist motion affects the precision of the grip force. Therefore, the fact that there was an insignificant difference in the wrist angular velocity at ball release at three speeds ensures the same force-producing capacity of the extrinsic finger muscles at ball release irrespective of the ball speed. In addition, the time series of the wrist angular velocity between -80 ms and 0 ms was also kept relatively constant irrespective of the ball speed.

By virtue of this wrist kinematics, the extrinsic finger muscles can produce the finger grip force following the same time schedule irrespective of the ball speed even under the circumstances that the finger grip force must be scaled to a back force from the ball that is proportional to the hand acceleration (Hore et al. 1999, 2001).
This would reduce the CNS’s load of having to change the finger control programs from throw to throw. To confirm this hypothesis, it would be necessary to show some correlation between the target hitting performance and the wrist kinematic variability. The present study does not show this correlation, probably because the throwing task was relatively easy. A throwing task that requires more accurate finger control would be necessary.
Appendix

Two-joint throwing

Elbow

\[
\text{NET}_e = + \ddot{\theta}_1 \left[ I_1 + I_2 + m_2 l_2^2 + m_1 r_1^2 + m_2 r_2^2 + 2m_2 l_1 r_2 \cos \theta_2 \right]
\]

\[
\text{INT}_e = - \ddot{\theta}_2 \left[ I_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2 \right]
\]

\[
+ \dot{\theta}_2^2 [m_2 l_1 r_2 \sin \theta_2]
\]

\[
+ \dot{\theta}_1 \dot{\theta}_2 [2m_2 l_1 r_2 \sin \theta_2]
\]

\[
- \ddot{x}_e [(m_2 l_1 + m_1 r_1) \cos \theta_1 + m_2 r_2 \cos(\theta_1 + \theta_2)]
\]

\[
- \ddot{y}_e [(m_2 l_1 + m_1 r_1) \sin \theta_1 + m_2 r_2 \sin(\theta_1 + \theta_2)]
\]

\[
\text{GRA}_e = - g [(m_2 l_1 + m_1 r_1) \sin \theta_1 + m_2 r_2 \sin(\theta_1 + \theta_2)]
\]

\[
\text{MUS}_e = \text{NET}_e - \text{INT}_e - \text{GRA}_e
\]

Wrist

\[
\text{NET}_w = + \ddot{\theta}_2 \left[ I_2 + m_2 r_2^2 \right]
\]

\[
\text{INT}_w = - \ddot{\theta}_1 \left[ I_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2 \right]
\]

\[
- \dot{\theta}_2^2 [m_2 l_1 r_2 \sin \theta_2]
\]

\[
- \ddot{x}_e [m_2 r_2 \cos(\theta_1 + \theta_2)]
\]

\[
- \ddot{y}_e [m_2 r_2 \sin(\theta_1 + \theta_2)]
\]

\[
\text{GRA}_w = - g [m_2 r_2 \sin(\theta_1 + \theta_2)]
\]

\[
\text{MUS}_w = \text{NET}_w - \text{INT}_w - \text{GRA}_w
\]
$$I_i = \text{moment of inertia about the center of gravity, } r_i = \text{distance to center of mass from proximal joint of the segment, } l_i = \text{length, } m_i = \text{mass (} i = 1: \text{forearm, } 2: \text{hand)} \text{, } \ddot{x}_e = \text{linear acceleration of the elbow for horizontal direction, } \ddot{y}_e = \text{linear acceleration of the elbow for vertical direction. The mass of the ball is included in the hand mass.}$$
Three-joint throwing

**Shoulder**

\[
\begin{align*}
\text{NET}_s &= + \phi_1 
\begin{bmatrix}
I_1 + I_2 + I_3 + \\
\frac{m_2 \ell_1^2}{I_1} + \frac{m_3 \ell_2^2}{I_1} + \frac{m_3 \ell_3^2}{I_1} + m_1 r_1^2 + m_2 r_2^2 + m_3 r_3^2 + \\
(2m_3 l_1 l_2 + 2m_2 l_1 r_2) \cos \phi_2 + 2m_3 l_2 r_3 \cos \phi_3 + 2m_3 l_1 r_3 \cos(\phi_2 + \phi_3)
\end{bmatrix} \\
\text{INT}_s &= - \phi_2 
\begin{bmatrix}
I_2 + I_3 + \\
m_3 l_2 r_3 \cos \phi_3 + m_3 l_1 r_3 \cos(\phi_2 + \phi_3)
\end{bmatrix} \\
&- \phi_3 
\begin{bmatrix}
I_3 + \\
m_3 r_3^2 + m_3 l_2 r_3 \cos \phi_3 + m_3 l_1 r_3 \cos(\phi_2 + \phi_3)
\end{bmatrix} \\
&+ \phi_2^2 [l_1((m_3 l_2 + m_2 r_2) \sin \phi_2 + m_3 r_3 \sin(\phi_2 + \phi_3))] \\
&+ \phi_3^2 [m_3 l_2 r_3 \sin \phi_3 + m_3 l_1 r_3 \sin(\phi_2 + \phi_3)] \\
&+ \phi_1 \phi_2 [2l_1((m_3 l_2 + m_2 r_2) \sin \phi_2 + m_3 r_3 \sin(\phi_2 + \phi_3))] \\
&+ \phi_1 \phi_3 [2m_3 l_5 (l_2 \sin \phi_3 + l_1 \sin(\phi_2 + \phi_3))] \\
&+ \phi_2 \phi_3 [2m_3 l_5 (l_2 \sin \phi_3 + l_1 \sin(\phi_2 + \phi_3))] \\
&- \ddot{x}_s 
\begin{bmatrix}
(m_3 l_1 + m_3 l_1 + m_1 r_1) \cos \phi_1 + \\
(m_3 l_2 + m_2 r_2) \cos(\phi_1 + \phi_2) + m_3 r_3 \cos(\phi_1 + \phi_2 + \phi_3)
\end{bmatrix} \\
&- \ddot{y}_s 
\begin{bmatrix}
(m_3 l_1 + m_3 l_1 + m_1 r_1) \sin \phi_1 + \\
(m_3 l_2 + m_2 r_2) \sin(\phi_1 + \phi_2) + m_3 r_3 \sin(\phi_1 + \phi_2 + \phi_3)
\end{bmatrix} \\
\text{GRA}_s &= - g 
\begin{bmatrix}
(m_2 l_1 + m_3 l_1 + m_1 r_1) \sin \phi_1 + \\
(m_3 l_2 + m_2 r_2) \sin(\phi_1 + \phi_2) + m_3 r_3 \sin(\phi_1 + \phi_2 + \phi_3)
\end{bmatrix}
\end{align*}
\]

\[
\text{MUS}_s = \text{NET}_s - \text{INT}_s - \text{GRA}_s
\]
Elbow

\[
\text{NET}_e = + \begin{bmatrix}
I_2 + I_3 + \\
m_3 l_2^2 + m_2 r_2^2 + m_3 r_3^2 + \\
2m_3 l_2 r_3 \cos \phi_3
\end{bmatrix} \\
\text{INT}_e = - \begin{bmatrix}
I_2 + I_3 + \\
m_3 l_2^2 + m_2 r_2^2 + m_3 r_3^2 + \\
(m_3 l_1 l_2 + m_2 l_1 r_2) \cos \phi_2 + 2m_3 l_2 r_3 \cos \phi_3 + m_3 l_1 r_3 \cos(\phi_2 + \phi_3)
\end{bmatrix} \\
\begin{bmatrix}
I_3 + \\
m_3 r_3^2 + \\
m_3 l_2 r_3 \cos \phi_3
\end{bmatrix} \\
- \dot{\phi}_3^2 \left[ l_1 (m_3 l_2 + m_2 r_2) \sin \phi_2 + m_3 r_3 \sin(\phi_2 + \phi_3) \right] \\
+ \dot{\phi}_1 \dot{\phi}_3 [2m_3 l_2 r_3 \sin \phi_3] \\
+ \dot{\phi}_2 \dot{\phi}_3 [2m_3 l_2 r_3 \sin \phi_3] \\
- \ddot{x}_1 \left[ (m_3 l_2 + m_2 r_2) \cos(\phi_1 + \phi_2) + m_3 r_3 \cos(\phi_1 + \phi_2 + \phi_3) \right] \\
- \ddot{y}_2 \left[ (m_3 l_2 + m_2 r_2) \sin(\phi_1 + \phi_2) + m_3 r_3 \sin(\phi_1 + \phi_2 + \phi_3) \right] \\
\text{GRA}_e = - g \left[ (m_3 l_2 + m_2 r_2) \sin(\phi_1 + \phi_2) + m_3 r_3 \sin(\phi_1 + \phi_2 + \phi_3) \right] \\
\text{MUS}_e = \text{NET}_e - \text{INT}_e - \text{GRA}_e
\]
Wrist

\[
\text{NET}_w = \phi_3 \left[ I_3 + m_3 r_3^2 \right] \\
\text{INT}_w = - \phi_1 \left[ I_3 + m_3 r_3^2 + m_3 l_2 r_3 \cos \phi_3 + m_3 l_1 r_3 \cos (\phi_2 + \phi_3) \right] \\
- \dot{\phi}_2 \left[ I_3 + m_3 r_3^2 + m_3 l_2 r_3 \cos \phi_3 \right] \\
- \dot{\phi}_1^2 \left[ m_3 r_3 (l_2 \sin \phi_3 + l_1 \sin (\phi_2 + \phi_3)) \right] \\
- \dot{\phi}_2^2 \left[ m_3 l_2 r_3 \sin \phi_3 \right] \\
- \phi_1 \dot{\phi}_2 \left[ 2 m_3 l_2 r_3 \sin \phi_3 \right] \\
- \ddot{x}_s \left[ m_3 r_3 \cos (\phi_1 + \phi_2 + \phi_3) \right] \\
- \ddot{y}_s \left[ m_3 r_3 \sin (\phi_1 + \phi_2 + \phi_3) \right] \\
\text{GRA}_w = - g \left[ m_3 r_3 \sin (\phi_1 + \phi_2 + \phi_3) \right] \\
\text{MUS}_w = \text{NET}_w - \text{INT}_w - \text{GRA}_w
\]

Symbols

\(I_i\) = moment of inertia about the center of gravity, \(r_i\) = distance to center of mass from proximal joint of the segment, \(l_i\) = length, \(m_i\) = mass \((i = 1: \text{upper arm}, 2: \text{forearm}, 3: \text{hand})\), \(\ddot{x}_s\) = linear acceleration of the shoulder for horizontal direction, \(\ddot{y}_s\) = linear acceleration of the shoulder for vertical direction. The mass of the ball is included in the hand mass.
References


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Figure 1: Experimental setup and joint angles in two-joint throwing (A) and three-joint throwing (B). The positive direction of each angular displacement is the counterclockwise direction. Note that the throwing motion consists of the elbow extension (negative direction) and wrist flexion (negative direction) for two-joint throwing, and the shoulder extension (negative direction), elbow extension (negative direction) and wrist flexion (negative direction) for three-joint throwing.
Figure 2: Data for representative single trials in two-joint throwing for slow (left), medium (center), and fast condition (right) from subject A are shown. A: Stick pictures at -100, -75, -50, -25, 0 ms are drawn. The target is in the right direction. B: joint angles at the wrist (dashed line) and elbow (solid line). C: joint angular velocity at the wrist (dashed line) and elbow (solid line). D: the net torque (solid line), gravity torque (dashed line), muscle torque (gray line), and interaction torque (dotted line) at each joint. The vertical lines at 0 ms represent the ball-release time. Four vertical dotted lines represent -100, -75, -50, -25 ms.
Figure 3: A: Interaction torque plotted against the muscle torque from movement onset to ball release of the same trial as Fig. 2. The IOCIMs (index of coordination between INT and MUS) are also shown. B: Interaction torque plotted against the muscle torque from movement onset to ball release of all trials for all subjects in two-joint throwing. The IOCIMs averaged for all subjects are also shown.
Figure 4: Data for representative single trials in three-joint throwing for slow (left), medium (center), and fast condition (right) from subject A are shown. A: Stick pictures at -100, -75, -50, -25, 0 ms are drawn. The target is in the right direction. B: joint angles at the wrist (dashed line) and elbow (solid line), and shoulder (thick line). C: joint angular velocity at the wrist (dashed line) elbow (solid line), and shoulder (thick line). D: the net torque (solid line), gravity torque (dashed line), muscle torque (gray line), and interaction torque (dotted line) at each joint. The vertical lines at 0 ms represent the ball-release time. Four vertical dotted lines represent -100, -75, -50, -25 ms.
Figure 5: A: Interaction torque plotted against the muscle torque from movement onset to ball release of the same trial as Fig. 4. The IOCIMs (index of coordination between INT and MUS) are also shown. B: Interaction torque plotted against the muscle torque from movement onset to ball release of all trials for all subjects in three-joint throwing. The IOCIMs averaged for all subjects are also shown.
Figure 6: Muscle torque impulse (MUSIm), interaction torque impulse (INTIm), net torque impulse (NETIm) from movement onset to ball release, and angular velocity at ball release for each joint in two-joint throwing. S, slow; M, medium; F, fast. * $P < 0.05$ (Tukey’s post-hoc multiple comparison test)
Figure 7: Muscle torque impulse (MUSIm), interaction torque impulse (INTIm), net torque impulse (NETIm) from movement onset to ball release, and angular velocity at ball release for each joint in three-joint throwing. S, slow; M, medium; F, fast. * $P < 0.05$ (Tukey’s post-hoc multiple comparison test)