Control of Joint Rotations in Overarm Throws of Different Speeds Made by Dominant and Nondominant Arms

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INTRODUCTION

Although some principles have been identified by which the CNS controls hand movements between two targets at different speeds, it is not known whether these principles apply for the control of more complex multijoint movements such as throwing a ball. When moving the hand between two targets, subjects tend to make straight hand paths with bell-shaped velocity profiles irrespective of the hand speed (e.g., Abend et al. 1982; Atkeson and Hollerbach 1985; Hollerbach and Flash 1982; Soechting and Lacquaniti 1981). This and other evidence supports the idea that such speed-invariant kinematics result from a centrally planned hand trajectory and preplanned compensation for interaction torques (e.g., Flash and Hogan 1985; Gordon et al. 1994; Gribble and Ostry 1999; Pigeon et al. 2003a; Sainburg et al. 1999). In 1982, Hollerbach and Flash proposed a simple strategy by which the CNS could preprogram the dynamics in this situation. In this scheme, the speed-dependent and gravity-dependent torque profiles are generated by two separate force drives that can be separately scaled. A movement can be produced r times faster by scaling the speed-dependent torque profile by r². Such an operation involves time-scaling, i.e., the movement duration is varied by scaling in time. A feature of time-scaling is that neither the hand path nor the interjoint coordination pattern should change in movements of different speeds.

Although time-scaling appears to apply for two-dimensional (2-D) point-to-point hand movements, it is unclear whether it also applies for more complex 3-D arm movements. In agreement with time-scaling, in a 3-D arm reaching task made from a seated position, Nishikawa et al. (1999) found no effect of arm movement speed on hand path curvature and arm postures. Similarly, in another seated study in which subjects made a wide variety of reaching movements with some chest movement at normal and fast speeds (Zhang and Chaffin 1999), there was no effect of movement speed on either the joint angle or the interjoint coordination pattern. However, because there were slight differences in the normalized displacement and velocity profiles for the two speeds of movement, which were similar to those previously described by Zelaznik et al. (1986) and Nagasaki (1989), it was concluded that in the strictest sense time-scaling was not present in joint kinematics. In tasks involving large body motion together with arm reaching or pointing, most studies have found violations of time-scaling, i.e., that there is an effect of speed on hand path and arm joint kinematics. For example, in voluntary reaching movements made at fast and slow speeds from the standing position, the shapes of the hand paths were different (Pozzo et al. 2002), and the angular excursions of body segments were larger in the fast movements (Thomas et al. 2003). Similarly, in a standing reach-and-turn task, there were differences in interjoint coordination in fast and slow movements (Pigeon et al. 2003b). In many of these situations, there were discrepancies with time-scaling, although in some cases, they were relatively small. One possibility is that the discrepancies occurred because subjects were not highly skilled at these tasks, i.e., time-scaling was not perfect, and consequently, there was a failure to properly compensate for interaction torques.

Another multijoint movement that requires precise coordination of body and arm is overarm throwing. Throwing is somewhat different from reaching and pointing in that it is performed with different degrees of skill by different subjects. Whether time-scaling of joint rotations applies for overarm throwing is unknown. The requirement of time-scaling that joint amplitudes remain constant in throws of different speeds has been found in skilled throws for finger opening (Hore et al. 1994; Sainburg et al. 1999; Gribble and Ostry 1999; Pigeon et al. 2003b). In many of these experiments, there were discrepancies with time-scaling, although in some cases, they were relatively small. One possibility is that the discrepancies occurred because subjects were not highly skilled at these tasks, i.e., time-scaling was not perfect, and consequently, there was a failure to properly compensate for interaction torques.
1999b, 2001) and wrist flexion (Debicki et al. 2004). It follows that time-scaling may apply for overarm throwing. A further possibility is that the more skilled the throw, the more precisely time-scaling would apply. Consequently, we tested the hypothesis that overarm throws of different speeds are made by time-scaling of joint rotations, i.e., by joint rotations that have the same positions and amplitudes but that are scaled in time. The hypothesis was tested by examining joint rotations of both dominant and nondominant overarm throws made by different arms of the same skilled throwers. The results showed that, in contrast to the hypothesis, dominant arms showed major differences between fast and slow throws in the pattern of joint rotations.

**METHODS**

**General procedures**

Eight subjects participated in these experiments, which were approved by the local ethics committee. All subjects gave informed consent. Subjects were 20- to 25-yr-old males who were skilled at throwing (Hw, Sm, Fs, Ob, Ry, Gy, Ht, Kn). Most had played competitive baseball in their youth. All reported that they were skilled at throwing with their dominant right arm and unskilled with their nondominant left arm. Experiments were performed in which they threw with their right arm on 1 day and their left arm on another day. In both experiments, they made natural overarm throws with body rotation and with a backswing and horizontal forward motion of the upper arm. Throws were made from a standing position with one foot forward and the feet stationary. Subjects threw baseballs (150 g) on command about every 20 s at a vertical grid of 6-cm numbered squares (9 cm wide × 27 cm high). The center aimed target was a 6-cm square at about eye level and about 2.5 m from the hand at ball release. Each throw was scored for accuracy by the subject calling out the square that was struck. On the rare occasions when throws made with the nondominant arm missed the target grid, the throw was repeated. Subjects made 30 medium, 30 slow, and 30 fast throws in that order. The instruction was to throw at a consistent speed and accurately. Fast throws were to be made fast and accurately bearing in mind that they had to make 30 throws at this speed.

The timing of ball release from the hand grip (onset of ball rolling on the fingers) and from the tip of the middle phalanx (final ball release) was measured with two pressure-sensitive microswitches (triggers) that were attached to the proximal and distal phalanges of the middle finger. Subjects were instructed to grip the ball so that they applied pressure to the proximal switch and to release the ball from the middle finger so that the ball rolled over the distal switch. The timing accuracy of the distal microswitch was verified by comparing it with the time of onset of finger flexion after finger extension, which is a moment that is known to coincide with release of the ball from the fingertips (e.g., Hore et al. 1999b). Ball speed was measured with a radar gun (Stalker Professional Sports Radar; sampling rate 100/s) that was located about 4 m behind the target curtain, i.e., about 6.5 m from the hand at ball release.

**Recording of angular (but not translational) positions of arm segments**

Angular positions of five arm segments were measured using the search-coil technique as described previously (e.g., Hore et al. 1996a, 1999b). This technique was employed because it allowed accurate measurement of joint angles in the fast throws. Although the search-coil technique records angular motions of arm segments robustly and with great precision, it does not record translational motion. Furthermore, in this study in which subjects made unconstrained throws from a standing position, translational motion could not be calculated because the chest was not stationary. Search coils were secured 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, and the sternum. Subjects stood in three orthogonal alternating magnetic fields of frequency 62.5, 100, and 125 Hz 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 in 3-D space.

Two coordinate systems were used to describe arm motion. First, when considering angular positions of arm segments in space, we used a space-fixed coordinate system in which motions were described as components of rotations around axes aligned with the magnetic fields (Hore et al. 1996a). In this study, as far as hand path was concerned, only vertical motion of the hand was analyzed. Hand angular position was the vertical component of hand motion in space around the space-fixed medial-lateral horizontal axis (Fig. 1A). Second, 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. It is important to appreciate that joint motions do not represent components of vertical motion around a space-fixed horizontal axis. Rather, joint motions were computed as joint rotations, e.g., elbow motion was calculated from forearm motion with respect to upper arm motion irrespective of upper arm orientation in space. The joint motions that we measured were wrist flexion, elbow extension, radioulnar pronation, and rotation at the shoulder. As before (Hore et al. 1996a), rotations at the shoulder (Fig. 1B) were described as shoulder roll (rotation of the upper arm around its own long axis where forward roll corresponds to shoulder internal rotation), shoulder elevation (up-down motion of the upper arm with respect to the body irrespective of shoulder azimuth position), and shoulder azimuth (horizontal rotation of the upper arm with respect to the body). All joint angles were defined as being 0° when the arm was in a reference position, with the upper arm horizontal and lateral and with the forearm, hand, and fingers vertical in a straight line with the palm forward (Fig. 1A).

**RESULTS**

**Throwing performance of the dominant and nondominant arms**

There were large differences in throwing performance between the dominant and nondominant arms. As instructed, subjects were able to throw the ball at three different speeds with both the dominant arm (Fig. 2A) and the nondominant arm (Fig. 2B). Repeated-measures ANOVAs showed a significant main effect of the instruction speed on ball speed for both the dominant and nondominant arms (P < 0.001). In both cases, Tukey’s post hoc multiple comparison test indicated significant differences between all speeds in the two arms. Across-subject comparison of the means of the slow, medium, and fast speeds for the dominant and nondominant arms revealed that, in each case, throws with the dominant arm were faster (paired t-test, P < 0.01 in all cases). These mean values for the dominant arm were as follows: slow, 38 km/h (SD 4); medium, 55 km/h (3); fast, 88 km/h (8). For the nondominant arm, the values were as follows: slow, 31 km/h (3); medium, 40 km/h (3); fast, 53 km/h (5). Ball impact location on the target was more variable for throws with the nondominant arm. For the high-low direction, mean ball impact heights and SD for 30 throws made by each subject at each speed instruction are shown for the dominant arm in Fig. 2C and the nondominant arm in Fig. 2D. Zero represents the height of the aimed target. Means of the magnitudes of the SD across subjects are shown on the right. For
each throwing speed, these magnitudes were larger for throws with the nondominant arm (paired t-test, all \( P < 0.05 \)). On the basis of the maximum ball speeds achieved in the fast condition and the variability of ball impact on the target at all speeds, for these subjects, the dominant arm can be considered to be skilled, whereas the nondominant arm is unskilled.

**Throws with the dominant arm**

Figure 3 shows the time-varying joint rotations of a single fast throw and a single slow throw made by the dominant arm of a representative subject (Gy). The vertical component of hand angular position in space for these two throws is shown in Fig. 3A and the corresponding joint rotations in Fig. 3, B–G. The fast throw is given by a thin trace; the slow throw by a thick trace. Both throws are aligned on the moment of ball release (\( \text{time 0} \)). Although the hand in space (Fig. 3A) goes through similar amplitudes of angular motion during the forward throw (forward-up) to ball release (long vertical line at \( \text{time 0} \)) in the fast and slow throws, the underlying joint rotations are very different. For example, for the fast and slow throws, joint positions at ball release are different for elbow extension (Fig. 3C), shoulder roll (Fig. 3F), and shoulder azimuth (Fig. 3G). Similarly, joint starting positions (which were the moment when joint velocity crossed a threshold of 200°/s and which are marked by short vertical lines) are different in the fast and slow throws for wrist flexion (Fig. 3B) radioulnar pronation (Fig. 3D), shoulder roll (Fig. 3F), and shoulder azimuth (Fig. 3G).

The hypothesis is that overarm throws of different speeds are made by time-scaling of joint rotations. One way to test this is to plot one joint rotation against another, i.e., in joint space, which removes the time dimension. The hypothesis predicts that angular position joint space plots for fast and slow throws will overlap, i.e., that joint starting positions and amplitudes will be the same for throws of different speeds. Given that we recorded six joint rotations, it is possible to plot each joint rotation against every other joint rotation, i.e., there are many 2-D representations of 6-D joint space. Figure 4A shows three 2-D joint space plots of 10 consecutive fast throws (mean ball speed, 97 km/h) and 10 consecutive slow throws (mean, 33 km/h) made by the dominant arm of the same subject (Gy). Plots were chosen to occur over equivalent ranges of joint rotation by going back 300 ms from ball release in the slow throws and 100 ms in the fast throws. Arrows indicate the direction of the joint rotation in the forward throw; traces end at ball release. Figure 4A shows two important points about dominant arm throws. First, the pattern of joint rotations is strikingly different in the fast and slow throws in each of the three 2-D plots. Second, the pattern of joint rotations for each set of fast or slow throws is consistent.

To quantify these differences in joint rotations between throws of different speeds made by the dominant arm, we measured a number of different joint angular position parameters for each of the six joint rotations. The first was joint angular position at ball release. The mean and SD of joint angular positions at ball release for each joint rotation for the 30 slow, 30 medium, and 30 fast throws are shown for the dominant arm of each subject in Fig. 5. The means across subjects are shown at the right. In Fig. 5, 0° is given by the horizontal line, subjects are shown at the bottom, and slow, medium, and fast are shown from left to right for each subject. Considering all joint angular positions at ball release, Fig. 5 shows that there were consistent differ-
ences across subjects, e.g., fast throws had mean wrist positions that were more flexed (Fig. 5A) and mean elbow positions that were more extended (Fig. 5B). To determine whether the effects in Fig. 5 were statistically significant, we performed a multivariable ANOVA (MANOVA) using SPSS. Initially, we considered six joint angles at ball release. The factors were speed (3 levels) and arms (2 levels). However, the interaction of speed and arm (dominant and nondominant) was statistically significant \(F(12,16) = 6.49, P < 0.001\), which indicated that the joint angles behaved inconsistently across speeds in the two arms. Consequently, we analyzed the two arms with separate MANOVAs. For the dominant arm, with three levels of speed, the test of within subjects effects gave \(F(12,16) = 6.49, P < 0.001\). Considering the individual joint rotations, there was a statistically significant main effect at the \(P < 0.05\) level of throwing speed on joint position at ball release for wrist flexion, elbow extension, shoulder elevation, shoulder roll, and shoulder azimuth. Only radioulnar rotation was not statistically different, but this may have been because the arm has to adopt a similar degree of pronation in throws of all speeds for the ball to hit the target.

**FIG. 2.** Ball speed and ball target accuracy for 30 throws made by the dominant and nondominant arms of all subjects. S, slow; M, medium; F, fast. C and D: ball high-low accuracy on the target is given by the mean target height struck by the ball \(\pm SD\). Zero (horizontal line) represents the height of the aimed target. Means of the magnitudes of the SD are shown on the right.

**FIG. 3.** Time-varying traces of hand angular position and 6 joint rotations for single fast and slow throws made by a dominant (skilled) arm. Traces aligned on ball release. Subject Gy.
It could be argued that joint positions are different at ball release because of differences in the points of ball release on the hand path for throws of different speeds rather than because of differences in the joint rotations themselves. Consequently, we also measured angular joint positions at the moment in the throw when the hand was vertical in space. This point, which results from the rotations at shoulder, elbow, and wrist, occurs near ball release but does not depend on the timing of ball release. Again, for the skilled arm at this hand, vertical point a main effect of throwing speed on joint position was found at the $P < 0.05$ level for wrist flexion, elbow extension, shoulder elevation, shoulder roll, and shoulder azimuth.

We also measured joint angular positions at the onset of each joint motion during the forward throw (short vertical lines on the traces in Fig. 3). For shoulder roll in the fast throws (Fig. 3F), when two periods of forward motion (i.e., shoulder internal rotation) occurred, the point nearest to the onset of elbow extension was taken as the onset. For the dominant arm, a statistically significant effect at the $P < 0.05$ level of throwing speed on joint position at onset was found for wrist flexion, radioulnar pronation, shoulder roll, and shoulder azimuth. We also calculated the amplitude of joint excursion. The effect of throwing speed on joint amplitude in the forward throw to ball release for skilled throws was only significant for elbow extension.

Close inspection of Fig. 3 reveals that there are some differences between joint rotations in the fast and slow throws that are not captured by this analysis. One that may be of importance in the generation of arm and ball speed in the fast throws is a brief, rapid period of shoulder roll in the forward direction (shoulder internal rotation) just before ball release (Fig. 3F). This can also be seen for the fast throws in the joint space plots of shoulder roll plotted against elbow extension and shoulder azimuth against shoulder azimuth (Fig. 4A).

We next investigated whether these major differences in the pattern of joint rotations in throws of different speeds made by the dominant arm were associated with differences in hand path. As described in METHODS, for unconstrained standing throws, the search-coil technique does not allow measurement or calculation of hand translational path. However, one parameter of hand motion that is measured by the search-coil technique is hand angular path. Figure 6A shows the vertical component of hand angular path (i.e., that component which occurred around the medial-lateral horizontal axis; Fig. 1A), for a slow, medium, and fast throw made by subject Ht. Traces have been aligned on the moment in the throw when the hand was vertical in space (solid horizontal line). Over the 150-ms period, traces are different because of the different speeds of the throws. Figure 6B shows the same three traces after they were time-scaled. Each throw was time-scaled to the fastest
throw made by subject Ht based on ball speed. For example, the time-scaling factor for the medium speed throw in Fig. 6A was obtained by dividing its speed (66 km/h) by the speed of the fastest throw made by subject Ht (111 km/h), which gave 0.59. For the slow throw, the time-scaling factor was 0.44 (49 divided by 111), and for the fast throw, it was 0.95 (105 divided by 111). In Fig. 6B, the time axis after scaling is 159 ms for the fast throw, 252 ms for the medium throw, and 340 ms for the slow throw. After time-scaling, the three traces appear to show considerable overlap, especially in the forward phase of the throw (forward-up direction). To examine this...
quantitatively, for each throw, we determined the value of time that corresponded to 20 ms on the time-scaled trace and measured the hand angular position at this point. In Fig. 6B, the time-scaled 20-ms point is shown as the vertical dashed line on the time-scaled axis of 150 ms. For subject Ht, the values for each set of 30 throws at the time-scaled 20-ms point were as follows: slow, 74.5° (SD 1); medium, 72.2° (2); fast, 70.3° (1). Figure 6C shows values for all subjects. A repeated-measures ANOVA showed that, across subjects, there was no main effect of throwing speed instruction on hand angular position \( [F(2,6) = 0.097, P = 0.91] \). Similarly, no main effect was found at three further time-scaled points: 15 \( (P = 0.92), 10 \) \( (P = 0.89) \), and 5 ms \( (P = 0.98) \). Although this is an interesting result, it does not address the question of whether the translational hand paths (which determine ball direction) are different in throws of different speeds. This issue will have to await further study using techniques to measure hand translation. In summary, in throws of different speeds made by the skilled arms, the quantitatively different joint angular position paths were associated with similar hand angular position paths in the forward (vertical) direction after the latter were time-scaled based on ball speed.

**Throws with the nondominant arm**

In contrast to throws with the dominant arm that showed marked differences in joint motions for fast and slow throws, throws with the nondominant arm showed relatively small differences. For example, Fig. 4B shows 2-D joint space plots for the nondominant arm of subject Gy for the same pairs of joints that are shown for the dominant arm in Fig. 4A. Although the traces for the fast and slow throws made by the nondominant arm are not the same, i.e., they do not always overlap, the differences between them are small compared with those in Fig. 4A. A second example showing this point for the nondominant arm is shown in Fig. 7B. This figure gives four joint space plots of averages of the 30 slow, 30 medium, and 30 fast throws from subject Hw. For comparison, the equivalent joint
space plots for the dominant arm of Hw are shown on the left (Fig. 7A). The direction of the forward throw is shown by arrows; traces end at ball release. These average joint space plots for the nondominant arm show small differences for the throws of different speeds compared with those of the dominant arm.

To determine whether across subjects statistically significant differences occurred in the joint rotations for throws of different speeds made by the nondominant arm, we performed the same analysis as for the dominant arm. Considering joint angular position at ball release, Fig. 8 shows that, across subjects, only some joints showed consistent differences for throws of different speeds, e.g., compared with the reference position (0°), in the fast throws, shoulder roll (Fig. 8E) was more externally rotated (rotated more backward), and shoulder azimuth (Fig. 8F) was rotated less forward. In agreement, the MANOVA showed that, of the six joints in the nondominant arms, only shoulder roll and shoulder azimuth showed an effect at the $P < 0.05$ level of throwing speed on joint angular position at ball release. Considering other joint angular positions for the nondominant arms, statistically significant effects were found for three joints at hand vertical, two at joint onset, and none for joint amplitude.

These smaller effects of speed for the nondominant arm were not because ball speeds were similar for the slow, medium, and fast instructions (Fig. 2B). Similarly, it could not be explained by fast throws in the nondominant arm having the same speeds of arm joint rotations as the slow throws and the increased speed being produced entirely by increased trunk rotation. This can be seen for elbow extension. Across subjects, maximum elbow extension velocities at or before ball release for the nondominant arm throws were as follows: slow, 688°/s (SD 69); medium, 932°/s (105); fast, 1,336°/s (108). The equivalent values for the dominant arm throws were as follows: slow, 804°/s (71); medium, 1,173°/s (84); fast, 1,952°/s (115).

Although across subjects there were statistically significant differences in the nondominant arms for a few joint angular positions, the magnitudes of the differences between the fast and slow throws were a lot less than for the dominant arms (Figs. 4, 5, 7, and 8). To investigate this further we simplified the situation by omitting the medium throws. Figure 9 shows a comparison across subjects of the differences in angular positions between the fast and slow throws for each of the six joint rotations for the nondominant arms (left side of each pair) and the dominant arms at ball release (Fig. 9A) and at the hand vertical position (Fig. 9B). For example, for elbow extension (Fig. 9A), across subjects, the mean difference between the angular position at ball release for the fast and slow throws was <1° for the nondominant arms, whereas it was about 22° for the skilled arms. A repeated-measures ANOVA showed that, across joints, these joint amplitude differences between fast and slow throws of the dominant and nondominant arm were statistically significant for ball release [$F(6,2) = 46.18, P < 0.05$] and for hand vertical [$F(6,2) = 196.35, P < 0.01$] but were not significant for joint onset [$F(6,2) = 4.73, P = 0.18$].

Finally, the question arose of whether these differences in joint angular positions across speeds for the two arms would occur if the speeds of the throws were the same. This was possible to test because the mean of the dominant arm slow throws (38 km/h) was similar to the mean of the nondominant arm medium throws (40 km/h); the mean of the dominant arm medium throws (55 km/h) was similar to the mean of the nondominant arm fast throws (53 km/h). When these two sets of speeds were considered, a MANOVA showed that there was an interaction between speed and arm (dominant and nondominant) for elbow extension [$F(1,7) = 8.33, P < 0.05$] and for
Effect of speed on joint rotations in nondominant arm throwing

Does time-scaling of joint rotations apply for overarm throwing? For the nondominant arm, the answer depended on the joint that was considered. The rationale we used to answer this question was that, if time-scaling were to apply, joint space plots would be the same for throws of different speeds. In keeping with this, in the nondominant arm, joint space plots were often similar in throws of different speeds (Figs. 4B and 7B). Across subjects, at the moment of ball release, there were no statistically significant differences at the $P < 0.05$ level for the nondominant arm in angular positions for wrist flexion, elbow extension, radioulnar pronation, and shoulder elevation.

This was not because arm (ball) speeds were similar in the nondominant arms for the different speed instructions. Across subjects, the mean ball speed was 1.7 times larger in the fast (53 km/h) compared with the slow (31 km/h) nondominant throws. Also, it was not because velocities of joint rotations in the nondominant arms were similar in the throws of different speeds. Across subjects, the mean maximum elbow extension velocity at or before ball release was 1.9 times larger in the fast compared with the slow nondominant throws.

Although evidence was found for time-scaling in the nondominant arm, in some cases, the evidence showed that time-scaling did not apply. Across subjects, there was a small but significant effect at ball release of throwing speed on shoulder roll and shoulder azimuth. The direction of this effect was the same as that found in dominant arm throws, i.e., in fast throws at ball release there was less internal rotation at the shoulder (Figs. 5E and 8E) and less forward-left horizontal rotation (Figs. 5F and 8F). One explanation of these findings is that the nondominant arms were not completely unskilled but displayed some rudimentary elements of the pattern shown by skilled arms.

This raises the issue of the meaning of the term “unskilled.” We considered the nondominant arm to be unskilled because of its greater inaccuracy (Fig. 2, C and D) and because the speed of its fast throws (53 km/h) was much less than fast throws made by the dominant arm (88 km/h; Fig. 2, A and B). Nevertheless, it could be argued that to throw at 53 km/h with the nondominant arm requires a considerable degree of skill in arm and arm-body coordination. This ability of the nondominant arm may come from day-to-day use, from previous throwing experience with the nondominant arm, and from transfer of knowledge about throwing mechanisms (techniques) gained with the dominant arm (Crismimagha-Heminger et al. 2003; Teixeira 2000).

One mechanism in the nondominant arm that could be considered to be skilled is the control of interaction torques. That is, for similar traces to occur in joint space in throws of different speeds (Figs. 4B and 7B), there must have been precise central preprogramming to compensate for the effects of interaction torques at the different joints. This is a significant ability for the nondominant arm in throwing given that its fast speeds were of the order of 5–10 times faster than “fast” arm motions in other studies of the dominant arm. For example, in fast turn-and-reach movements, peak finger velocity was about 6 km/h (Pigeon et al. 2003a). This ability of the nondominant (unskilled) arm in throwing was equivalent to the dominant arm performing a variety of shoulder-elbow reaching tasks of different speeds where invariance of joint rotations, or something close to it, has been found (e.g., Lacquaniti and Soechting 1982; Soechting and Lacquaniti 1981; Zhang and Chaffin 1999). The explanation that has been proposed for invariance of hand paths and joint positions in motions of different speeds (kinematic invariance), is that the CNS predictively compensates for interaction torques (e.g., Gribrle and Ostry 1999; Hollerbach and Flash 1982; Koshland et al. 2000; Pigeon et al. 2003a). In this context, it would not be surprising if some of the differences that occurred in joint rotations between slow and fast throws in the nondominant arm were caused by a failure to perfectly compensate for interaction torques in the fast throws.

In summary, the results for the nondominant arm have shown that time-scaling may apply for some joint rotations (wrist flexion, elbow extension, radioulnar pronation, shoulder
elevation), but not for others (shoulder roll, shoulder azimuth). There are at least three possible explanations for the observed deviations from time-scaling. The first is that planning of throws did not occur by time-scaling. This is a plausible conclusion but does not explain why many joint rotations of the nondominant arm showed similarities in joint space in throws of different speeds, especially compared with those of the dominant arm. The second is that time-scaling applies for unskilled throwing but that the present nondominant arms were skilled to some extent in that they displayed some rudimentary elements of the pattern shown by skilled arms. As discussed, some evidence supports this explanation. The third possibility is that time-scaling applies for these unskilled throws but there was incomplete compensation for interaction torques. We conclude that in the strictest sense, time-scaling does not apply for all joints in these nondominant arms. Nevertheless, the finding that many joint space patterns for the nondominant arm were not greatly different from those predicted by time-scaling raises the possibility that time-scaling may apply for a completely unskilled arm, i.e., an arm that is experienced in day-to-day reaching tasks but has no experience in throwing.

Effect of speed on joint rotations in dominant arm throwing

Although the nondominant arm achieved considerable speeds with joint rotations that resembled those predicted by time-scaling, the results clearly showed that time-scaling did not apply for the dominant arm, i.e., in the dominant arm joint rotations were markedly different for throws of different speeds. Put another way, a fast throw was not a slow throw whose joint positions and amplitudes remained constant but whose joint velocities were sped up. This was not expected for throwing given the previous findings that the amplitude of finger opening (Hore et al. 1999b, 2001) and the amplitude of wrist flexion (Debicki et al. 2004) were constant in throws of different speeds. Furthermore, if joint rotations were to be different in dominant arm throws of different speeds, it might have been expected that fast throws would have had larger joint amplitudes and therefore longer times to accelerate the ball. In fact, elbow extension followed this pattern, but it was the only joint rotation to do so. The more striking difference in joint rotations between fast and slow throws of the dominant arm was the difference in starting and finishing positions and the difference in the overall pattern of joint rotations (Figs. 4A and 7A). One clear example was shoulder roll in dominant arms, where the starting and finishing positions were different in throws of different speeds and where there was often a brief shoulder internal rotation before ball release in the fast throws that was not seen in the slow throws (Figs. 3F and 4A).

Despite these different patterns of joint angular positions in throws of different speeds, the shape of the hand angular (vertical) paths were similar when they were time-scaled. This occurred in part because the differences in joint rotations in fast and slow throws tended to cancel each other out. For example, although in dominant arm fast throws at ball release, the wrist was more flexed and the elbow more extended (Fig. 5), at the shoulder, the upper arm was more externally rotated. Presumably, this contributed to the achievement of similar angular hand positions at ball release, which is required for ball accuracy on the target.

We attempted to minimize any differences in orientation of hand paths in space that will occur in throws of different speeds by placing the target a short distance from the subject (see METHODS). Considering the mean slow and fast throws made by the dominant arm across subjects, the difference in the drop of the ball because of gravity of 22.4 cm (calculated from 0.5$gt^2$) resulted in an orientation difference at the shoulder of 4.1°. This difference would be expected to occur only in shoulder elevation (Watts et al. 2004) and is small compared with other joint angle differences observed between the slow and fast throws made by the dominant arm, e.g., >20° for shoulder roll and elbow extension (Fig. 9A, black bars). Consequently, release angle differences cannot account for the joint angle differences and lack of time-scaling in throws made by the dominant arm.

Although these results for the dominant arm showed that variable relations occurred in joint space in throws of different speeds, a previous study showed that one speed-invariant relation did occur in such throws (Hore and Watts 2005). This was between the vertical component of hand angular position in space (hand angular path) and finger opening at the proximal interphalangeal joint. For these two parameters, a fast throw was the same as a slow throw that was sped up. This was taken to support the idea that precisely timed finger opening in overarm throwing depends, not on a central timing controller, but on a central spatial controller that matches angular positions of finger opening to the intended hand path. Given that time-scaling can produce similar hand angular (vertical) paths (Fig. 6), it follows that finger opening could also be time-scaled to give the speed-invariant relation between these two parameters. In addition, other factors such as the shape of the hand translatinal path, may also be taken into account by the central spatial controller.

Comparison with reaching and pointing tasks

A picture starts to emerge about the pattern of joint rotations in arm movements of different speeds when findings are considered from a variety of different tasks of increasing complexity and increasing speeds. When the task involved only two joints, joint rotations were similar in fast and slow movements (Hollerbach and Flash 1982; Lacquaniti and Soechting 1982; Soechting and Lacquaniti 1981). The same applied for seated 3-D pointing (Nishikawa et al. 1999). For seated 3-D reaching with trunk movement, joint rotations were similar but small differences were noted (Zhang and Chaffin 1982; Soechting and Lacquaniti 1981). When the task became more complex and involved body and arm movements in which subjects made reaching movements by bending forward, clear differences were seen in segment motions (Thomas et al. 2003). Similarly, in a pointing task in 3-D to remembered targets, Adamovich et al. (1999) found that a change in movement speed (from 4.3 to 9.7 km/h) significantly influenced the final elbow angle and the arm elevation angles. However, these two effects canceled each other out leaving final arm position invariant with respect to movement speed. A similar result was obtained by Pigeon et al. (2003b). They found in slow and fast turn-and-reach movements that, for most subjects, the shape of the finger trajectory was preserved, whereas there were differences in the underlying interjoint coordination. However, these joint differences varied from subject to subject, and in some subjects did not occur. In contrast, for overarm throws made by the dominant arm (Fig. 5), the joint differences between fast and slow throws

Effect of speed on joint rotations in dominant arm throwing

Although the nondominant arm achieved considerable speeds with joint rotations that resembled those predicted by time-scaling, the results clearly showed that time-scaling did not apply for the dominant arm, i.e., in the dominant arm joint rotations were markedly different for throws of different speeds. Put another way, a fast throw was not a slow throw whose joint positions and amplitudes remained constant but whose joint velocities were sped up. This was not expected for throwing given the previous findings that the amplitude of finger opening (Hore et al. 1999b, 2001) and the amplitude of wrist flexion (Debicki et al. 2004) were constant in throws of different speeds. Furthermore, if joint rotations were to be different in dominant arm throws of different speeds, it might have been expected that fast throws would have had larger joint amplitudes and therefore longer times to accelerate the ball. In fact, elbow extension followed this pattern, but it was the only joint rotation to do so. The more striking difference in joint rotations between fast and slow throws of the dominant arm was the difference in starting and finishing positions and the difference in the overall pattern of joint rotations (Figs. 4A and 7A). One clear example was shoulder roll in dominant arms, where the starting and finishing positions were different in throws of different speeds and where there was often a brief shoulder internal rotation before ball release in the fast throws that was not seen in the slow throws (Figs. 3F and 4A).

Despite these different patterns of joint angular positions in throws of different speeds, the shape of the hand angular (vertical) paths were similar when they were time-scaled. This occurred in part because the differences in joint rotations in fast and slow throws tended to cancel each other out. For example, although in dominant arm fast throws at ball release, the wrist was more flexed and the elbow more extended (Fig. 5), at the shoulder, the upper arm was more externally rotated. Presumably, this contributed to the achievement of similar angular hand positions at ball release, which is required for ball accuracy on the target.

We attempted to minimize any differences in orientation of hand paths in space that will occur in throws of different speeds by placing the target a short distance from the subject (see METHODS). Considering the mean slow and fast throws made by the dominant arm across subjects, the difference in the drop of the ball because of gravity of 22.4 cm (calculated from 0.5$gt^2$) resulted in an orientation difference at the shoulder of 4.1°. This difference would be expected to occur only in shoulder elevation (Watts et al. 2004) and is small compared with other joint angle differences observed between the slow and fast throws made by the dominant arm, e.g., >20° for shoulder roll and elbow extension (Fig. 9A, black bars). Consequently, release angle differences cannot account for the joint angle differences and lack of time-scaling in throws made by the dominant arm.

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were large, occurred in all subjects, and were always in the same direction. In summary, as the movement task progressively changed from a relatively slow two joint planar task to a very fast 3-D overarm throw, differences became increasingly apparent in the underlying joint rotations in fast and slow movements.

CNS planning

If only the reaching and pointing tasks with the dominant arm and the unskilled throwing with the nondominant arm are considered, it could be suggested that time-scaling applies in all cases, but that as the task becomes more complex and faster, the compensation for interaction torques becomes less accurate, which results in differences in interjoint coordination. However, this suggestion does not seem to apply for skilled dominant arm throwing, where large and consistent differences occurred across subjects in joint angular positions in fast and slow throws (Fig. 5). Instead, the likely explanation for all reaching, pointing, and throwing findings is that the highest priority in CNS planning is preservation of hand path and that interjoint coordination is subservient to this goal (cf., Flash and Hogan 1985; Gordon et al. 1994; Krakauer et al. 2000; Paninski et al. 2004). The evidence indicates that this is the case when arm reaching is combined with trunk movement (Ma and Feldman 1995; Pigeon and Feldman 1998; Pigeon et al. 2003b; Wang and Stelmach 1998). It would also be expected to apply for skilled throwing where the ball follows the translational path of the hand in space until just before ball release (Watts et al. 2004).

The question of how the CNS plans and controls hand paths is an ongoing issue (see Flash and Sejnowski 2001; Sabes 2000; Scott 2003 for recent reviews). The finding of speed-invariant hand paths has been taken as evidence for kinematic planning, but the underlying neural control mechanisms are hotly debated (Feldman and Latash 2005; Ostry and Feldman 2003). According to equilibrium point theory, if movement is planned in terms of static postures, time can be scaled to achieve a range of speeds (Bizzzi et al. 1992; Feldman 1966). Alternatively, speed-invariant hand paths can be explained by force control models (Atkeson and Hollerbach 1985; Buneo et al. 1994; Flanders and Herrmann 1992; Gottlieb et al. 1996; Hollerbach and Flash 1982; Koshland et al. 1999). A further view (Todorov and Jordan 2002) is that certain invariant features of arm movement tasks do not result from computational shortcuts in the motor planning but rather are emergent properties of a system that uses optimal feedback control.

In contrast to the nondominant arm, throwing with the dominant arm was associated with a different pattern of joint rotations in throws of different speeds, i.e., it was not speed invariant. If movement planning for skilled throwing occurs in an extrinsic frame of reference centered on the hand, development of the skill of throwing fast would be associated with the achievement of an optimal sequence of arm joint motions for producing maximal ball speeds given this hand path. At the level of joint angular positions, this is associated at ball release in fast throws with wrist positions that are more flexed, elbow positions that are more extended, and shoulder positions that are more externally rotated (Fig. 5). One joint motion that has been associated with fast skilled throwing and is not present in fast unskilled throwing is deceleration of elbow extension before ball release (Hore et al. 2005). Elbow extension deceleration has been proposed to cause forearm translational deceleration, which in turn, would cause a whip-like increase in wrist flexion velocity (Debicki et al. 2004). If this were the case, it would be an example of an exploitation of interaction torques to increase ball speed. Other mechanisms for exploitation of interaction torques could occur at the elbow and shoulder though the situation is complex (Hong et al. 2001).

Considerable insight has been obtained into the nature of the control signals to the dominant and nondominant arms in multijoint movements. A study of the greater ball inaccuracy in throws of the same speed with the nondominant arm showed that there was greater variability in joint rotations at both proximal and distal joints than in throws with the dominant arm, although it was the variability at the distal joint (finger) that caused the ball inaccuracy (Hore et al. 1996b). It was suggested that this was caused by a lack of precision in the commands to the nondominant arm. More specifically, it has been proposed that there are differences in the neural control of limb dynamics between the dominant and nondominant arms (Sainburg 2002). In multijoint reaching, the dominant arm shows advantages in preplanning the limb trajectory (open-loop control), whereas the nondominant arm is specialized for closed-loop feedback mechanisms responsible for final position accuracy (Bagesteiro and Sainburg 2003). Further understanding of the nature of these signals has come from a study of single joint elbow extensions. Evidence was found that the system controlling the dominant arm does so through preplanning mechanisms that specify pulse-height control of the initial acceleration, whereas the system controlling the nondominant arm does so largely through feedback mediated pulse-width control (Sainburg and Schaefer 2004). These findings help explain why most subjects use the dominant arm in fast throwing where large pulses of activity are needed to produce rapid acceleration of joints and where there is no time for peripheral feedback (Hore et al. 1999a). It is not known whether practice can alter the strategies used by each limb. However, based on these dynamic control differences it can be speculated that even with large amounts of practice the nondominant arm would never be able to throw as fast as the dominant arm.

In summary, this study investigated the pattern of joint rotations that underly skilled and unskilled throwing. From the technical perspective, a strength was that in these very fast throws (≥110 km/h) joint rotations were accurately measured at 1,000 Hz; a weakness was that it was not possible to determine hand translational paths. The major finding was that for the dominant (skilled) arm time-scaling of joint rotations did not apply, i.e., across subjects, skilled fast throws showed large and consistent differences in the pattern of angular position joint rotations compared with skilled slow throws. These same throws showed similar hand angular paths when they were time-scaled based on ball speed. In contrast, although the nondominant (unskilled) arm showed statistically significant differences at ball release in the rotation at two of its joints, overall the pattern at most joints was similar to that predicted by time-scaling. To interpret these kinematic results, further studies are required in which hand translation is recorded and torques are calculated. The hypothesis we propose for future study is that as subjects are first learning to throw fast with their dominant arm they use time-scaling of joint rotations. Development of skill at this stage would involve learning to generate the correctly shaped and scaled dynamic muscle torques to compensate for interaction torques. This strategy, however, will
only achieve ball speeds that are about one-half those of a skilled arm. We further hypothesize that in the continuing development of skill for throwing fast, time-scaling is superseded by a more complex pattern of interjoint coordination that produces additional arm speed, in part, by exploiting interaction torques.

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