Intersegmental dynamics shape joint coordination during catching in typically developing children but not in children with developmental coordination disorder

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Intersegmental dynamics shape joint coordination during catching in typically developing children but not in children with developmental coordination disorder. J Neurophysiol 111: 1417–1428, 2014. First published January 8, 2014; doi:10.1152/jn.00672.2013.—Factors shaping joint coordination during multijoint movements were studied using a one-handed ball-catching task. Typically developing (TD) boys between 9 and 12 yr of age, at which catching becomes consistently successful, and boys with developmental coordination disorder (DCD) of the same age participated in the study. The arm was initially stretched down. Catching was performed by flexing the shoulder and elbow and extending the wrist in the parasagittal plane. Catching success rate was substantially lower in children with DCD. Amplitudes and directions of joint motions were similar in both groups. Group differences were found in shoulder and elbow coordination patterns. TD children performed the movement predominantly by actively accelerating into flexion, one joint at a time—first the elbow and then the shoulder—and allowing passive interaction torque (IT) to accelerate the other joint into extension. Children with DCD tended to accelerate both joints into flexion simultaneously, suppressing IT. The results suggest that the TD joint coordination was shaped by the tendency to minimize active control of IT despite the complexity of the emergent joint kinematics. The inefficient control of IT in children with DCD points to deficiency of the internal model of intersegmental dynamics. Together, the findings advocate that joint coordination throughout a multijoint movement is a by-product of the control strategy that benefits from movement dynamics by actively accelerating a single joint and using IT for rotation of the other joint. Reduction of control-dependent noise is discussed as a possible advantage of this control strategy.

HUMAN MOVEMENTS ARE USUALLY multijoint, which means they involve rotation of more than a single joint. Principles used by the central nervous system to coordinate joint motions remain under debate. The need for such principles for control of movements with redundant degrees of freedom (DOFs) was recognized by Bernstein (1967). DOF redundancy allows performance of a task with different combinations of DOF motions, and principles underlying the selection of a single combination out of many possibilities need to be understood. Some freedom in coordination of joint motions also exists when the number of DOFs is not redundant. An example is arm movements performed with rotation of the shoulder and elbow in the horizontal plane. Although the target dictates specific joint amplitudes, different joint-velocity profiles can be used, resulting in different coordination patterns of joint motions.

A frequently observed coordination pattern involves simultaneous acceleration and deceleration of the joints with bell-shaped velocity profiles. However, there are movements in which this pattern is not observed. For example, the shoulder and elbow were accelerated and decelerated simultaneously in the horizontal plane during rhythmic line drawing, only when the movements were performed with flexion at one joint combined with extension of the other joint (Dounskaia et al. 2002a). During line drawing, which required simultaneous flexion and simultaneous extension of the two joints, there was a lag of the elbow with respect to the shoulder. Similarly, a lag of the shoulder with respect to the elbow was found during a reaching movement in the sagittal plane (Konczak and Dichgans 1997). The lag was pronounced in adults, and it gradually emerged in infants during development of reaching. These examples show that control principles underlying joint coordination are more complex than a simple rule to accelerate-decelerate the joints simultaneously (Morasso 1981).

Our recent findings suggest that joint coordination may be, to a large extent, an emergent property of control of movement dynamics. With the use of a free-stroke drawing task that provided freedom in the selection of movement direction, Goble et al. (2007) revealed a preference to perform horizontal arm movements by organizing joint control in a specific way. The preference was to use either the shoulder or elbow as the leading joint, i.e., to rotate it actively, by muscle torque (MT) and allow the produced interaction torque (IT) to rotate the other (trailing) joint, predominantly passively. The preference for this joint-control strategy was confirmed in a number of later studies (Dounskaia and Goble 2011; Dounskaia et al. 2011; Wang and Dounskaia 2012; Wang et al. 2012). Wang and Dounskaia (2013) also show that the preferred control strategy dominates during three-dimensional (3D) arm movements by capitalizing on the redundancy of DOFs that allows the use of this strategy for a wide range of tasks. Evidence that this strategy also prevails during reaching movements in 3D was provided by Ambike and Schmiedeler (2013) and Vandenberge et al. (2010). It was also shown that during tasks that required suppression of IT by MT at the trailing joint, there was a tendency to deviate from the task and deform the movement to allow a larger contribution of IT to the trailing joint rotation (Dounskaia et al. 1998, 2002b).
These studies suggest that the preference to perform arm movements by rotating either the shoulder or elbow actively and to use IT maximally for rotation of the other joint may be a fundamental control principle that overrules the principle of kinematic simplicity that supports simultaneous acceleration and deceleration of both joints. The goal of the present study was to test this prediction. Shoulder-elbow movements that involve flexion at one joint and extension at the other joint could not be used for this purpose, because the simultaneous acceleration and deceleration of both joints are performed with the preferred joint-control pattern (Dounskaia et al. 2002a; Galloway and Koshland 2002; Levin et al. 2001). Thus we needed to study a movement that requires either flexion or extension of both joints. A movement with these properties used in the present study was one-handed ball catching. If the arm is initially stretched down along the side of the body, catching a ball at the eye level requires flexion of both the shoulder and elbow. Nevertheless, the joints are not accelerated and decelerated simultaneously during skillful performance of this movement (Mazyn et al. 2006; Savelsbergh and Whiting 1996). We examined whether joint coordination during this movement can be accounted for by the preference to rotate one joint actively and exploit IT for rotation of the other joint.

Skillful, one-handed catching emerges in boys at the age of ~10 yr, as evident by a success rate at the task that approaches 95% (Fischman et al. 1992). We therefore analyzed joint dynamics during catching a ball by typically developing (TD) boys of 9–12 yr of age. To highlight control principles underlying developed movements in TD children, less skillful performance was tested in a group of boys with developmental coordination disorder (DCD) of the same age. Children with DCD demonstrate below-age-level performance in skilled and coordinated tasks despite a typical level of intelligence and no neurological abnormalities (American Psychiatric Association 2000). Ball catching is a skill that the majority of children with DCD has difficulty performing (Utley and Astill 2007; Van Waaelvelde et al. 2004; Wright and Sugden 1996). Lack of coordination of the arm’s joints has been proposed to be one of the major reasons for low success rate (Przysucha and Maraj 2010). We hypothesized that skillful catching, demonstrated by TD children, is performed with shoulder and elbow coordination different from the simultaneous flexion of the two joints and that the produced joint coordination is accounted for with the preferred joint-control strategy that includes active acceleration/deceleration of one joint and the use of IT for acceleration/deceleration of the other joint. We also hypothesized that children with DCD have a reduced ability to use this joint-control strategy.

**METHODS**

**Participants**

Nine TD boys between the ages of 9 and 12 (mean = 10.6 yr; SD = 1.08) and 10 boys with DCD in the same age range (mean = 11.0 yr; SD = 1.16) participated in the study. The TD group included one left-handed participant. In the DCD group, three boys were left handed. The dominant hand was determined by observing which arm the participant used to write his name and verified by asking which hand he used to catch a ball. The TD children were recruited from a school in the surrounding area of the university. The children with DCD were recruited through the Motor Development Clinic at Lakehead University. This research was approved by Lakehead University’s Research Ethics Board. Written, informed consent was obtained from all participants and their respective parents or guardians.

For the TD children to be included in the study, they had to have no coordination problems, as evident from the total impairment score (TIS) above 20% in relation to the normative data supplied by the Movement Assessment Battery for Children (MABC) (Henderson and Sugden 1992). On average, this group was above this threshold (mean = 61.3%; SD = 2.53). Also, their DCD Questionnaire (DCDQ) (Wilson et al. 2007) scores were, on average, >57 (mean = 61.8; SD = 7.21), indicating that these children had no coordination problems that would interfere with their academic achievement and/or activities of daily living. Lastly, all of the parents of the TD children did not indicate on the consent form that their children had a medical condition interfering with their coordination or an intellectual impairment.

The process of recruiting children with DCD follows. The director of the Motor Development Clinic identified children in the clinic’s databases based on low MABC score and invited their parents/guardians to contact the researchers for potential participation in the study. The children who decided to participate were included if they satisfied the following four DCD-related diagnostic criteria, according to the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (American Psychiatric Association 2000). First, the coordination problems of these children had to be substantially higher compared with their age-matched peers, which was confirmed by the TIS on the MABC as below 5% in relation to the normative data. For the selected group, the mean TIS was 1.1% (SD = 0.31). Second, the coordination problems that the children exhibited had to interfere with their academic achievement and/or activities of daily living, which was determined with the DCDQ score of <57. The mean value of this score in the DCD group was 44.2 (SD = 16.7). Third, the children could not have any known medical condition interfering with their coordination, such as a pervasive developmental disorder. This was verified by the director of the Motor Development Clinic, who had access to the developmental histories of the children. This criterion was also verified via questions on the consent form. Finally, the children had to have a typical level of intelligence [intelligence quotient >85 (Guzee et al. 2001)]. All individual scores are provided in Table 1. All recruited children were engaged in various forms of

<table>
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<tr>
<th>Participant</th>
<th>Group</th>
<th>Success</th>
<th>MABC TIS</th>
<th>MABC TBS</th>
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<tr>
<td>1 w/o DCD</td>
<td>80%</td>
<td>89th</td>
<td>More than 15th</td>
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<tr>
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<td>100%</td>
<td>96th</td>
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<td>70th</td>
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<td>70%</td>
<td>79th</td>
<td>More than 15th</td>
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<tr>
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<tr>
<td>19 DCD</td>
<td>20%</td>
<td>1st</td>
<td>Less than 5th</td>
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**ABC, Assessment Battery for Children; MABC, Movement ABC; TIS, total impairment score; TBS, total ball score; w/o, without; DCD, developmental coordination disorder.**
physical activity, including “ball skills,” which was a component of the program that children with DCD routinely practiced at the Motor Development Clinic. This factor eliminated a possibility that children with DCD performed ball catching less successfully than TD children merely because of insufficient practice.

Procedure
Participants completed two testing sessions on separate consecutive days. The first session involved administration of the MABC. The catching task was performed in the second session. Before task performance, a brief, verbal overview of what was required of the participant and a demonstration on how to perform the task were provided. The participant was standing in front of a tennis-ball machine at a distance of approximately 7–8 m. This distance was adjusted for each participant, such that participants would catch the ball approximately at eye level above the shoulder of the dominant arm. Before the ball was projected, the participant placed the foot ipsilateral to the dominant arm on a small marked spot on the floor. The arm was stretched down and relaxed. Following a “ready” command, the tennis-ball machine ejected a tennis ball at 7 m/s velocity at a 32.5° angle relative to the horizontal. Fifteen trials were performed. Five of the 10 remaining (acquisition) trials were practice trials. Five of the 10 remaining (acquisition) trials (trials 2, 4, 6, 8, and 10) were used for analysis. No constraints were imposed on shoulder, elbow, and wrist motion, but the trajectory of the ball was set up such that the arm movement would naturally occur in the parasagittal plane. The planarity of the arm movements was verified visually by the experimenter during performance. In addition, motion of the arm, approximately within the parasagittal plane, was confirmed after data acquisition was completed for a number of trials, randomly selected across participants. In all of these trials, the root mean square deviation from the parasagittal plane was <1 cm for the shoulder marker (see the marker description below), 3 cm for the elbow marker, 2 cm for the wrist marker, and 0.5 cm for the hand marker.

Data Recording
Two high-speed Hasselbl cameras were set up on the dominant side of the participant and calibrated to gather 3D coordinates of the passive reflective markers (Motus #9; Vicon Motus, Oxford, UK). The camera positions were chosen according to recommendations for optimal camera positioning (Allard et al. 1995). The data were collected at 100 Hz sampling frequency. A direct linear transformation (Peak Performance Technologies, Alpharetta, GA) of marker coordinates was used. The markers were attached to the greater trochanter (hip marker), acromion (shoulder marker), lateral epicondyle (elbow marker), styloid process of the ulna (wrist marker), and distal end of the fifth metacarpal (hand marker) of the participant’s dominant hand. The footage of the catching action was digitized semiautomatically using Vicon Motus software. To infer the beginning of the catching action, an infrared sensor was positioned at the mouth of the tennis-ball machine’s shaft. The sensor was attached to a circuit that was normally open, and when the tennis ball broke the infrared beam, the circuit closed and turned on a light-emitting diode light. This light was detected by both cameras, and it was used to synchronize the video footage manually during the trimming process. The data from the markers were filtered with a dual-pass second-order Butterworth filter with the cutoff frequency of 5 Hz.

Kinematic Analysis
The 3D coordinates of the markers were used to calculate shoulder, elbow, and wrist angles. Flexion of each joint was defined as an increase in the joint angle. Since the arm was initially stretched down at the child’s side, the catching movement required flexion (increases in the angle) at the elbow and shoulder and extension (decreases in the angle) at the wrist. Angular displacement, velocity, and acceleration were calculated for the shoulder, elbow, and wrist using software embedded in Vicon Motus. The beginning of each trial was defined as the point in time at which the shoulder or elbow angular velocity crossed a threshold of 5% of its maximal angular velocity. Movement termination was determined visually by examining the video of ball and arm motion produced by Vicon Motus. The end of movement was defined as either 30 ms after the ball contacted the hand or if the participant did not catch the ball, 30 ms after the ball passed the hand.

Kinetic Analysis
Kinetic analysis was performed to study joint control in the two participant groups. A simplified, planar model of the arm was used that included three rigid segments—the upper arm, forearm, and hand—and three DOFs in the parasagittal plane—shoulder flexion/extension, elbow flexion/extension, and wrist flexion/extension. The inverse dynamics equations were adapted from Hirashima et al. (2003) and are provided in the Appendix. The equations were used to compute joint torques from angular displacements, velocities, and accelerations of the shoulder, elbow, and wrist. Anthropometric measures were estimated for each child from total body mass and segment lengths using procedures formulated by Jensen (1986). Net torque (NT), IT, gravitational torque (GT), and MT were computed at each joint. NT is proportional to the angular acceleration of the joint. IT is passive, motion-dependent torque due to the mechanical interaction between moving segments of the arm. GT is torque attributed to the effect of gravity. MT was computed as the residual torque of NT, unexplained by IT and GT. MT is a result of active contraction of the muscles and of passive effects from soft tissues, such as tendons and ligaments, and from limitations of a joint’s range of motion.

The purpose of the kinetic analysis was to reveal the role of MT, IT, and GT in production of NT and thus in acceleration-deceleration of each joint. This was done by taking into account the torque relation, $NT = MT + IT + GT$. For example, if MT and NT had the same sign during a specific time period, this would suggest that MT contributed to joint acceleration during that time period. MT and NT having opposite signs would suggest that during that time period, the joint was accelerated by IT and/or GT, and MT dampened this acceleration. The contribution of MT, IT, and GT to NT was determined by calculating a signed torque impulse (Dounskaia et al. 2002a; Sainburg and Kalakanis 2000). For example, a positive impulse of MT was computed as the sum of absolute values of MT across all time moments at which MT coincided in sign with NT. Accordingly, a negative impulse of MT was computed as the negative sum of absolute values of MT across all time moments at which MT was opposite in sign to NT. The positive and negative impulses were then summed, yielding the total signed impulse of MT. Signed impulses of IT and GT were computed using the same method. The computation was applied to specific movement intervals distinguished during qualitative analysis of torque profiles presented in RESULTS.

In addition to the signed torque impulse, unsigned torque impulse was computed as a sum of absolute values of the torque across all time moments in a particular movement interval. This characteristic, normalized by unsigned torque impulse computed for the entire movement, resulted in relative unsigned torque impulse produced during the considered movement interval. The relative unsigned torque impulse gave insight into how much of a particular type of torque (MT, for example) was produced in a particular movement interval compared with the entire movement.

\[ NT = MT + IT + GT \]
Statistical Analysis

Independent sample t-tests were performed to compare computed kinematic and kinetic characteristics between the two groups. The α value was set at $P < 0.05$.

RESULTS

In terms of catching performance, it was found that children with DCD caught significantly fewer balls compared with TD children [$TD = 85\%$, $SD = 9.7\%$, vs. $DCD = 32\%$, $SD = 25.3\%$; $t_{(17)} = 6.18$, $P < 0.0001$]. Children with DCD also performed the movements slower than TD children [$TD = 0.72$ s, $SD = 0.07$, vs. $DCD = 0.83$ s, $SD = 0.08$; $t_{(17)} = 3.34$, $P < 0.01$]. With regard to joint kinematics, there were no significant differences in the initial angle of the shoulder [$TD = 19.1^\circ$, $SD = 1.74^\circ$, vs. $DCD = 18.2^\circ$, $SD = 3.1^\circ$; $t_{(17)} = 0.76$, $P > 0.1$], elbow [$TD = 18.7^\circ$, $SD = 6.5^\circ$, vs. $DCD = 18.1^\circ$, $SD = 3.3^\circ$; $t_{(17)} = 0.29$, $P > 0.1$], and wrist [$TD = -14.5^\circ$, $SD = 11.9^\circ$, vs. $DCD = -20.6^\circ$, $SD = 8.8^\circ$; $t_{(17)} = 1.28$, $P > 0.1$]. There were differences in the final angle at the shoulder [$TD = 10.6^\circ$, vs. $DCD = 11.9^\circ$; $t_{(17)} = 2.05$, $P < 0.05$]. The final elbow angles were also slightly different between the groups, but this difference did not reach significance [$TD = 68.5^\circ$, vs. $DCD = 68.0^\circ$; $t_{(17)} = 0.47$, $P > 0.1$]. No group differences were found in the final wrist angle [$TD = -30.8^\circ$, $SD = 10.6^\circ$, vs. $DCD = -24.8^\circ$, $SD = 7.5^\circ$; $t_{(17)} = 1.44$, $P > 0.1$]. Differences between the groups in angular amplitudes did not reach significance at any of the joints [$TD = 12.1^\circ$, vs. $DCD = 16.9^\circ$, $t_{(17)} = 2.05$, $P = 0.06$, at the shoulder; $TD = 69.4^\circ$, $SD = 7.2^\circ$, vs. $DCD = 72.3^\circ$, $SD = 16.6^\circ$, $t_{(17)} = 0.47$, $P > 0.1$, at the elbow; and $TD = 30.3^\circ$, $SD = 15.1^\circ$, vs. $DCD = 28.2^\circ$, $SD = 12.4^\circ$, $t_{(17)} = 0.33$, $P > 0.1$, at the wrist]. These results show that to catch the ball, both groups flexed the shoulder and elbow substantially, although children with DCD tended to decrease shoulder flexion and increase elbow flexion slightly. The movement also included moderate wrist extension. Next, we analyzed the contribution of different torques to joint motions.

Joint Control in TD Children

Since the movement involved flexion at the shoulder and elbow, it could be assumed that the two joints were flexed simultaneously. This movement pattern was not observed in TD children. Figure 1 exhibits time profiles of angular displacements at the shoulder, elbow, and wrist for a representative TD child. It is evident that the child did not flex the shoulder and elbow simultaneously but rather coordinated motions at these joints in a more complex pattern.

The NT profiles (that are proportional to joint accelerations) clarify the coordination pattern of the shoulder and elbow motions. Four phases of control can be distinguished from visual analysis of the shoulder and elbow NT in Fig. 1. First, positive NT was generated at both joints, signifying their simultaneous acceleration into flexion (phase 1). However, magnitudes of positive NT in phase 1 were small, and very soon, the shoulder NT became negative, accelerating the joint into extension (phase 2). Elbow NT mainly remained positive in phase 2. The negative peak of shoulder NT was followed by a large, positive peak, accompanied with a negative peak of elbow NT (phase 3). During the remaining movement portion, the sign of shoulder NT again switched to negative to decelerate shoulder flexion (phase 4). Elbow NT was low during phase 4, partially negative, and partially positive.

The described four phases in the shoulder and elbow NT were typical for movements of TD children. We visually analyzed each movement and found that these four phases were...
present in 60% of all movements in this group. The same control pattern, with small modifications in it, was used in the majority of the remaining movements. Namely, phase 1 was absent in 20% of movements, in which arm motion was initiated by joint control, typical of phase 2, i.e., elbow acceleration into flexion and shoulder acceleration into extension. In an additional 14% of movements, phase 2 was absent, because shoulder NT decreased at the end of phase 1, but instead of becoming negative, it again increased, producing the large wave of positive acceleration characteristic of phase 3. As in the four-phase pattern, the second positive wave of shoulder NT was accompanied by negative elbow NT. Accordingly, we distinguished phases 1 and 3 in these movements, using as a divider the minimal value of shoulder NT between the two positive peaks. Among the remaining 6% of movements, 4% had a single positive peak of shoulder NT, during which, elbow NT was first positive and then negative. For these movements, phase 1 was defined as the period during which both shoulder and elbow NTs were positive, and phase 3 was defined as the period during which shoulder NT was positive, and elbow NT was negative. No phase 2 was distinguished in these movements. Finally, phases 1–3 were not identifiable in 2% of movements, which was a single movement. This movement was excluded from further analyses.

Next, we analyzed the role of MT, IT, and GT in the production of NT at each joint during each of the four distinguished movement phases. In the example shown in Fig. 1, the acceleration into flexion, signified by positive NT in phase 1, was produced at both joints by positive MT, which also suppressed negative IT and GT. This type of control was brief, and it generated low NT. In phase 2, the elbow primarily continued to accelerate into flexion with both MT and IT contributing to this motion. At the same time, the shoulder was accelerated into extension predominantly passively, due to negative IT and GT, whereas positive MT was small. During phase 3, the shoulder was accelerated into flexion by large, positive MT. This shoulder motion resulted in large, negative IT at the elbow that was the primary cause of negative NT, i.e., acceleration into extension at the elbow. In phase 4, both joints were first accelerated into extension with a combined effect of MT and GT and then stabilized or performed a quick corrective action before the ball contact. This qualitative analysis shows that during phases 2 and 3, when most of NT was generated, shoulder and elbow control was reciprocal: while one joint was accelerated actively (by MT), the other joint was accelerated passively (primarily by IT).

The conclusions about the control of the shoulder and elbow during the four phases obtained from Fig. 1 were supported by the analysis of torque impulses calculated separately for each movement phase. The group averages of the impulses are shown in Fig. 2. The first two columns in each panel show unsigned and signed impulses of NT (NTIU and NTIS, respectively). The difference between them is that NITU was always positive if the corresponding torque predominantly assisted NT, and the sign was negative if the torque predominantly resisted NT. The vertical bars represent SD of the torque impulses.
positive, whereas the sign of NTIS depended on whether the joint was predominantly accelerated into flexion (positive) or extension (negative) during the considered phase. For this reason, NTIS was lower in magnitude than NTIU if NT changed its sign within the phase. MTI, ITI, and GTI in the last three columns show the amount of signed impulse of each MT, IT, and GT, respectively. In contrast to NTIS, the sign of these impulses did not depend on the direction of acceleration. Instead, it was positive or negative depending on whether the torque predominantly assisted or resisted NT during that phase. The scales in the y-axes was kept constant for each joint to allow the comparison of torque impulses across the phases.

In phase 1, both NTIU and NTIS were small at both the shoulder and elbow, indicating that little motion was produced. However, MTI was substantial, because in addition to generating NT, MT had to counteract IT and GT, as indicated by the negative signs of ITI and GTI. In phase 2, substantial, positive MTI was generated at the elbow. MT was the primary cause of positive NT (i.e., acceleration into flexion) at this joint. The shoulder was accelerated into extension (NTIS < 0) in this phase, and this was achieved by passive torques, IT and GT. In phase 3, the organization of joint control was opposite, such that the shoulder was accelerated into flexion by MT, whereas the elbow was predominantly accelerated into extension by IT and GT. In phase 4, GTI was positive, and it noticeably exceeded in magnitude both MTI and ITI, suggesting that GT was the primary contributor to NT. These torque-impulse results confirm that catching movements of TD children usually included four phases of shoulder and elbow movement coordination. Whereas the movement was typically initiated from simultaneous flexion at both joints, which required suppression of IT with MT, this phase was quickly cut short. The majority of joint flexion was performed sequentially—first at the elbow (phase 2) and then at the shoulder (phase 3). In each of these phases, the other joint passively accelerated into extension, predominantly due to IT generated by the actively moving joint.

With respect to the wrist, Fig. 1 shows that changes in wrist NT did not match the four-phase strategy of shoulder and elbow control. Instead, wrist NT was low and variable, and it resulted mainly from MT, which suppressed IT and created gradual extension of the joint throughout the course of the movement.

**Comparison of Joint Control Between TD Children and Children with DCD**

We investigated whether children with DCD performed catching movements by using the same four-phase pattern of joint control revealed in movements of TD children. First, we visually analyzed torque profiles during all movements of children with DCD. We found that many movements did not have the four-phase pattern. In fact, only 30% of the movements exhibited this type of joint control. Additionally, 8% of the movements included phases 2, 3, and 4 but not phase 1. Movements in which shoulder NT had two positive peaks, and phase 2 was absent represented 14% of all trials. The other type of movements without phase 2, which included a single positive peak of shoulder NT, during which elbow NT was first positive and then negative, was observed in 4% of trials. Finally, movements in which the four-phase pattern or its modifications were not distinguishable constituted 44% of all trials performed by children with DCD. We also noticed that there was high variability in the joint-control patterns in this group, both across and within participants.

Figure 3A exemplifies one of the most common joint-control patterns used by children with DCD instead of the four-phase pattern or its modifications. The profiles of the shoulder and elbow angular displacements show that both joints were flexed simultaneously. The torque profiles show that similar to phase 1 in movements of TD children, the movement started from simultaneous acceleration of the shoulder and elbow into flexion using MT at both joints. However, this phase was not cut short, as in movements of TD children, it continued until both joints completed acceleration into flexion. As a result, the entire acceleration into flexion was performed simultaneously at the shoulder and elbow, which required full suppression of IT with MT at each joint. This differed from the sequential acceleration into flexion, first of the elbow and then of the shoulder performed by TD children, during which IT was allowed to extend the other joint. The next part of the movement was passive deceleration of both joints, primarily by GT. This type of control continued until the end of the movement when the child, once again, briefly accelerated the shoulder and elbow actively into flexion, likely to make a corrective movement in an attempt to catch the ball. Although TD children also performed simultaneous deceleration of the shoulder and elbow (phase 4) by using GT, this movement portion in the child with DCD was much longer, as observed from a comparison of it between Figs. 3A and 1. Also, MT in Fig. 3A did not assist the joint deceleration at all, in contrast to phase 4 in TD children, as signified by positive MTI in Fig. 2. This representative example indicates that movements of this type unfolded with inefficient control of IT during shoulder and elbow acceleration into flexion and of GT during deceleration of the joints.

Another representative example of a movement pattern performed by children with DCD also demonstrates inefficiency of joint control (Fig. 3B). This child also started the movement by simultaneously accelerating the shoulder and elbow into flexion using MT. This initial flexion was cut short as in TD children. Joint control during the following movement portion, however, differed from that revealed in TD children. Instead of flexing the elbow by MT with assistance of IT and extending the shoulder by passive IT and GT (phase 2 in TD children), this child used MT and GT to accelerate the shoulder into extension and to suppress IT. At the same time, the elbow was also accelerated into extension, solely by GT. In the next phase, the child, once again, simultaneously accelerated the shoulder and elbow into flexion by MT while suppressing IT at each joint instead of using it as TD children did. The last phase was performed similarly to phase 4 in TD children, such that shoulder and elbow flexion was decelerated (NT < 0) with the use of GT. MT, however, assisted this deceleration at the shoulder only and not at the elbow, unlike in movements of TD children (Fig. 1). Thus the sequential flexion of the elbow and then shoulder that allowed minimal suppression of IT was not performed. Instead, the movement was performed predominantly through simultaneous flexion of the two joints and suppression of resistive IT. Control of GT during the final movement portion was also decreased.

Joint control was usually less efficient in the movements of children with DCD, even if the four-phase pattern were present. This can be observed in the example shown in Fig. 4. In phase 2, the elbow acceleration into flexion (positive elbow NT) was not assisted by IT, as in the movement of the TD child in Fig. 1. In
Trial-to-trial variability was significantly lower in TD children by each participant was compared between the two groups. The variability of this characteristic across the five trials performed confirmed this group difference [TD children with DCD compared with TD children]. The analysis peak, during which elbow NT was negative, was smaller in whether the portion of the duration of the highest shoulder NT elbow IT was exploited and not suppressed. We examined extent, by negative IT generated by shoulder motion; i.e., children. This negative elbow NT was produced, to a large peak was usually accompanied by negative elbow NT in TD on this peak. As illustrated in Fig. 1, the biggest shoulder NT was a common characteristic of the DCD group. Since a large, decreased ability to exploit intersegmental dynamics of the arm pressing IT instead of exploiting it. We examined whether the portion of the duration of the highest shoulder NT was the most consistent characteristic of joint control in both groups, we focused the analysis on this peak. As illustrated in Fig. 1, the biggest shoulder NT peak was usually accompanied by negative elbow NT in TD children. This negative elbow NT was produced, to a large extent, by negative IT generated by shoulder motion; i.e., elbow IT was exploited and not suppressed. We examined whether the portion of the duration of the highest shoulder NT peak, during which elbow NT was negative, was smaller in children with DCD compared with TD children. The analysis confirmed this group difference [TD = 0.79, SD = 0.13, vs. DCD = 0.57, SD = 0.28; \( t_{(17)} = 2.19, P < 0.05 \)]. In addition, variability of this characteristic across the five trials performed by each participant was compared between the two groups. The trial-to-trial variability was significantly lower in TD children compared with children with DCD [TD = 0.14, SD = 0.05, vs. DCD = 0.25, SD = 0.13; \( t_{(17)} = 2.35, P < 0.05 \)].

The inconsistency of the control patterns used by children with DCD prevented us from performing a similar analysis for the elbow NT. We therefore computed some torque characteristics at this joint for the entire movement. For example, the ratio of MT unsigned impulse (MTIU) to NTIU was computed. This ratio was informative about the amount of MT generated to produce NT throughout the movement. The mean value of this ratio was higher in children with DCD, supporting the possibility that elbow movement required more muscular effort from children with DCD compared with TD children. However, the group difference only approached but did not reach significance [TD = 2.85, SD = 0.45, vs. DCD = 3.62, SD = 1.17; \( t_{(17)} = 1.85, P = 0.08 \)]. Also, the ratio of the unsigned impulse of GT (GTIU) to NTIU at the elbow was significantly higher in children with DCD compared with TD children [TD = 1.93, SD = 0.36, vs. DCD = 2.87, SD = 1.03; \( t_{(17)} = 2.59, P < 0.05 \)], supporting the observation from the individual torque profiles that the influence of gravitation on movement production was stronger in children with DCD than in TD children. Together, the torque characteristics at the shoulder and elbow show that compared with TD children, movements of children with DCD were characterized by less effective exploitation of intersegmental dynamics of the arm for movement production, by reduced monitoring of GT, and by higher trial-to-trial variability of joint control.
A comparison of angular displacements and torque profiles at the wrist between Fig. 1 and Figs. 3 and 4 suggests that in both groups, wrist extension was limited, and MT largely compensated for IT and GT. However, motion at this joint in children with DCD was sometimes jerky, with abrupt peaks of NT, some of which were caused by IT (Fig. 3B) and some by MT (Fig. 4). This suggests that children with DCD were accelerating and decelerating the wrist to a higher magnitude throughout the catching action (i.e., their wrist motion was less smooth) compared with TD children. This conclusion was supported by a finding that children with DCD produced higher NT at the wrist through the entire movement compared with TD children. In particular, the mean percentage of trials that did not exhibit the four-phase pattern or any of its modifications was 47% in left-handers and 43% in right-handers. Also, the portion of the duration of the biggest shoulder NT peak, during which elbow NT was negative, was 0.73 in the left-handed TD child, which was similar to the mean value 0.77 (SD = 0.12) in the right-handed TD children. For children with DCD, this portion was even higher in left-handers compared with right-handers, although not significantly [0.62, SD = 0.36, and 0.54, SD = 0.27, respectively; t(8) = 0.38, P > 0.10]. Thus less efficient control of IT revealed in children with DCD cannot be accounted for with the higher portion of left-handed participants in this group but should be solely attributed to the effect of DCD.

DISCUSSION

We analyzed joint control during one-handed ball catching performed by TD children and children with DCD. The task required flexing the arm in the parasagittal plane. Although only two joints—the shoulder and elbow—were predominantly responsible for transporting the hand to the ball, the task was kinematically redundant, because participants had freedom in the temporal coordination pattern of motions at these joints. Since the final location of the hand required flexion at both the shoulder and elbow, it could be expected that these joint motions are performed simultaneously due to kinematic simplicity of this coordination pattern. Our alternative hypothesis was that the shoulder and elbow coordination is determined by a tendency to exploit intersegmental dynamics of the arm for movement production. The results supported this hypothesis, showing that TD children used a kinematically complex coordination pattern that used IT effectively. In contrast, the tendency to use the kinematically simplified coordination pattern was observed in movements of children with DCD. The joint-coordination patterns found in each group are discussed next.

Instead of flexing the shoulder and elbow simultaneously, TD children organized motion at these joints in a kinematically complex way. Four phases were distinguished in the movement based on changes in the sign of shoulder NT and hence, shoulder acceleration. The catching movement often started from simultaneous acceleration of both joints into flexion (phase 1). However, this phase was brief. The dominant portion of motion at the two joints was generated in phases 2 and 3, in which the two joints were accelerated into flexion sequentially—first the elbow and then the shoulder. Acceleration of each joint into flexion was performed actively by MT. At the same time, the other joint was accelerated into extension passively, predominantly by IT, with assistance of GT. Phase 4 included final deceleration of both joints, done with the use of the gravity effect, which was monitored by MT.

The sequential control pattern used during phases 2 and 3 cannot be accounted for with a tendency to move a single joint at a time and to “freeze” the other joint, because both joints

Fig. 4. Characteristics of a representative movement of a child with DCD performed with the 4-phase pattern typical of movements in TD children.

A comparison of angular displacements and torque profiles at the wrist between Fig. 1 and Figs. 3 and 4 suggests that in both groups, wrist extension was limited, and MT largely compensated for IT and GT. However, motion at this joint in children with DCD was sometimes jerky, with abrupt peaks of NT, some of which were caused by IT (Fig. 3B) and some by MT (Fig. 4). This suggests that children with DCD were accelerating and decelerating the wrist to a higher magnitude throughout the catching action (i.e., their wrist motion was less smooth) compared with TD children. This conclusion was supported by a finding that children with DCD produced higher NT at the wrist through the entire movement compared with TD children [TD = 4.00, SD = 1.61, vs. DCD = 6.52, SD = 3.29; t(17) = 2.08, P = 0.05].

Since some of our participants were left handed (one out of nine TD children and three out of 10 children with DCD), we examined whether the handedness factor influenced the differences in joint control between the two groups. No evidence for less efficient IT control in our left-handed participants compared with right-handed participants was found. For example, the single left-handed TD child used the four-phase pattern in all trials. Similarly, the three left-handed children with DCD had the same distribution of different control patterns in their trials as right-handed participants in this group. In particular, the mean percentage of trials that did not exhibit the four-phase pattern or any of its modifications was 47% in left-handers and 43% in right-handers. Also, the portion of the duration of the biggest shoulder NT peak, during which elbow NT was negative, was 0.73 in the left-handed TD child, which was similar to the mean value 0.77 (SD = 0.12) in the right-handed TD children. For children with DCD, this portion was even higher in left-handers compared with right-handers, although not significantly [0.62, SD = 0.36, and 0.54, SD = 0.27, respectively; t(8) = 0.38, P > 0.10]. Thus less efficient control of IT revealed in children with DCD cannot be accounted for with the higher portion of left-handed participants in this group but should be solely attributed to the effect of DCD.
were accelerated simultaneously—one actively and the other passively. Taking into account that acceleration into extension of the joints was in contradistinction to the eventual goal to flex both joints, this control pattern is also difficult to interpret based on considerations of movement kinematics. The reason for the emergence of this pattern becomes transparent from the consideration of movement dynamics. As a result of this strategy, IT assisted motion at both joints, whereas it would be suppressed by MT if both joints were accelerated simultaneously into flexion. This observation suggests that after the directions and amplitudes of shoulder and elbow motions required to bring the hand to the target spatial location were specified, the joint coordination during motion to the target location was determined by a specific strategy of control of intersegmental dynamics. Namely, only one joint at a time was accelerated actively, and IT generated by this motion was used for rotation of the other joint. According to this interpretation, effective use of intersegmental dynamics is a primary factor that determines organization of multijoint movement control.

A crucial contribution of peripheral biomechanics to movement production was predicted by Bernstein (1967). However, most theories of motor control view IT and its involvement in joint rotation as a by-product of other control principles. For example, one interpretation is that the spatial hand trajectory is specified first, followed by inverse kinematic transformations to determine time courses of joint excursions, and then MTs determined through inverse dynamics transformations (Hollerbach 1982; Morasso 1981). This approach is indifferent to whether IT is used effectively. Similarly, IT is a side effect of the equilibrium-point trajectory and spring-like muscle properties in the framework of the equilibrium-point hypothesis (Bizzi et al. 1992; Feldman 1986). Optimization of commonly considered criteria, such as muscle-energy expenditure and hand-trajectory smoothness (Todorov 2004), views IT as a by-product of the optimal control. It is difficult to account for the joint-coordination pattern that we observed in TD children with any of these theories.

The only theory that predicts effective exploitation of IT, in general, and the observed sequential pattern of shoulder and elbow control, in particular, is the leading joint hypothesis (LJH) (Dounskaia 2005, 2010). According to it, intersegmental dynamics plays a primary role in movement formation. Namely, a single (leading) joint is used to generate energy for the entire movement by producing IT, which rotates the other (trailing) joints. MT, at the trailing joints, can modify their passive motion, as required by the task. However, IT would be used maximally toward NT production if MT minimally interferes with it at the trailing joints.

A preference for this dynamically effective control strategy was demonstrated with a free-stroke drawing task [N. Dounskai and W. Wang (unpublished observations) and Dounskai and Goble (2011); Dounskai et al. (2011); Goble et al. (2007); Wang and Dounskai (2012); Wang et al. (2012)]. In these studies, participants produced a series of strokes, selecting the direction of each stroke in a random order. In spite of instructions that encouraged the uniform distribution of stroke directions, the distribution was consistently anisotropic. Strokes in the directions in which either the shoulder or elbow was rotated actively, and the other joint moved predominantly passively by IT were more frequent than strokes in the other directions. The similarity of the sequential joint-control pattern in phases 2 and 3 of the catching movements in TD children with the preferred joint-control pattern revealed during free-stroke drawing suggests that the sequential pattern was a result of the strategy to exploit IT for movement production by actively rotating one joint at a time and allowing IT to rotate the other trailing joint.

Previous studies addressing the leading joint-control strategy usually detected a single leading joint throughout the entire movement (Ambike and Schmiedeler 2013; Dounskai et al. 1998, 2002a, b; Galloway and Kosland 2002; Levin et al. 2001; Vandenberghe et al. 2010). The only exception was a horizontal swing of the arm, during which the trunk was the leading joint during the majority of the movement, and the shoulder took the lead at the end of the movement (Kim et al. 2009). The present study provides another example of a movement, during which the elbow and shoulder switch the roles. The elbow was leading, and the shoulder was trailing in phase 2, and the joints exchanged the roles in phase 3. This complicated organization of control of the catching movement supports our interpretation that effective use of passive biomechanical factors, such as intersegmental dynamics, is a primary principle of movement formation that is pursuit even at the expense of movement complexity.

Phase 4 was consistent with this interpretation, because gravity (another passive factor) was used during this phase for deceleration of both joints. However, the principle of dynamic effectiveness does not apply to the simultaneous acceleration of the shoulder and elbow into flexion during phase 1, because both IT and GT were suppressed by MT at both joints. Although there could be different reasons for the brief emergence of phase 1 in many movements of TD children, one possibility is that the control strategy that benefits from movement dynamics emerges gradually during development of catching. Phase 1 may be a rudimental feature that encompasses the entire movement during initial performance and then disappears gradually with improvements in the ability to anticipate and use IT. Indeed, the same catching movements performed by a single adult tested in this experiment (the data are not reported) included phases 2–4, not phase 1. A study of catching in adults and TD children of different ages is necessary to test this hypothesis reliably.

Shoulder and Elbow Coordination in Children with DCD

In contrast to TD children, who demonstrated the four-phase pattern or its modifications in 98% of all trials, this pattern was detected only in 56% of the trials performed by children with DCD. Simultaneous acceleration into flexion of the shoulder and elbow prevailed in the remaining trials. When the four-phase pattern was used, joint control capitalized on IT less effectively in the DCD group compared with the TD group. This conclusion was supported by the finding that the portion of the duration of the highest positive wave of shoulder NT (phase 3 in the four-phase pattern), during which elbow NT was also positive (both joints simultaneously accelerated into flexion), was significantly longer in children with DCD than in TD children. The high inter- and intrasubject variability of the joint-control pattern and the low success rate of catching in children with DCD suggest that the simultaneous acceleration into flexion of both joints was not a functional compensatory solution. Rather, this control pattern was implemented, because children with DCD were unable to develop a more optimal
pattern, such as that used by TD children of the same age. Optimality principles that may account for the sequential joint-control strategy during catching are discussed next.

Implications for Optimal Control of Multijoint Movements

The comparison of the performance of the catching movement between TD children and children with DCD suggests that active acceleration of one joint—the shoulder or elbow—and the use of IT produced by this motion to accelerate the other joint represent the optimal joint-control strategy. This conclusion is supported by the preference for this strategy during free-stroke production (Dounskaia et al. 2011; Goble et al. 2007). A reason why this strategy of control of multijoint movements may be preferred is that this strategy reduces noise in the control signal. Indeed, compensation for IT requires its accurate assessment before and during movement execution. Inaccuracy of sensory feedback would result in errors in the IT assessment. Also, IT is mutable and can be high in magnitude, and yet, MT has to match IT accurately for its compensation. Errors in the required timing and magnitude of MT would be an additional source of control-dependent noise. Both types of errors would make movements less accurate and would increase the cost of neural control required for coping with these errors (Harris and Wolpert 1998; Todorov and Jordan 2002).

The idea that the minimal interference of MT with IT at the trailing joints reduces control-dependent noise helps to understand better the findings of the present study. It suggests that by avoiding simultaneous acceleration into flexion of the shoulder and elbow during catching and instead, allowing the other joint to be accelerated into extension by IT and GT, TD children benefited from a more reliable joint-control pattern that provided a higher success rate. The poorer ability to use the optimal strategy of joint control in children with DCD contributed to high movement variability and low success rate.

Effect of DCD on Control of Multijoint Movements

In addition to supporting the novel interpretation of control of skillful multijoint movements, the results of this study help to interpret movement control in children with DCD. DCD occurs in ~5% of children (American Psychiatric Association 2000). It has been recognized that children with DCD perform less effective, qualitatively different movement patterns (Parker and Larkin 2003). A number of hypotheses have been proposed to specify the underlying cause of the motor impairment. Some studies suggested that the locus of the impairment is movement planning. This deficit causes increased reliance on visual information during movement performance (Rösblad and von Hofsten 1992; Van Waalvelede et al. 2006; Wann et al. 1998). However, processing of visual information is also deficient. During catching, children with DCD are unable to maintain focus on the ball and to predict the flight of the ball (Estil et al. 2002; Larkin and Hoare 1992; Lefebvre and Reid 1998). Other studies emphasized deficiency of neuromuscular mechanisms used during movement execution (Deconinck et al. 2006; Williams et al. 1983). Recently, kinematic analysis of catching prompted an additional hypothesis that intersegmental coordination creates one of the major causes of difficulties for children with DCD (Przysucha and Maraj 2010).

Whereas the majority of the suggested causes of the difficulties experienced by children with DCD remains hypothetical, our results make it clear that intersegmental coordination is deficient in this population. Furthermore, they point to the internal model of intersegmental dynamics as a control component, selectively problematic in children with DCD. Indeed, children in the DCD group flexed the shoulder and elbow and extended the wrist, according to the requirements of the catching task. This shows that children with DCD adequately planned direction and amplitude of motion at each joint. However, muscular control that implemented the kinematic plan was different in the two groups. Unlike TD children, children with DCD either did not use the control strategy that exploited IT for joint rotation, or they used it less effectively. The decreased ability to use IT for movement production points to deficiency of the internal model of movement dynamics that allows anticipation and control of internal and environmental forces (Shadmehr and Mussa-Ivaldi 1994; Wolpert and Kawato 1998). Thus our results advocate that children with DCD have a problem forming an internal representation of movement dynamics and not of movement kinematics. The largely intact representation of movement kinematics in children with DCD is supported by successful adaptation of these children to rotation of the visual field but only if the rotation is abrupt and not gradual (Kagerer et al. 2006). An abrupt visual-field rotation requires recalibration of the feed-forward mechanism that relates spatial locations with appropriate directions and amplitudes of joint motions. In contrast, small adjustments in joint kinematics during gradual rotation of the visual field may predominantly rely on current feedback (Abee and Bock 2003). The successful adaptation to abrupt but not gradual rotation of the visual field, therefore, supports the ability of children with DCD to plan representation of movement kinematics adequately.

The finding that children with DCD had trouble forming an internal representation of movement dynamics but not of movement kinematics is consistent with the interpretation of the LJH—that movement planning includes two stages. First, characteristics of joint motions necessary for fulfillment of the task are determined, such as directions and amplitudes of joint motions. Then, the leading joint-control strategy is used to specify the muscle-activation pattern that implements the kinematic plan while maximally exploiting passive dynamics for movement production. This interpretation implies that the coordination pattern of joint motions is determined by movement dynamics, not vice versa, as suggested by the theory of sequential inverse kinematics and dynamics transformations (Hollerbach 1982; Morasso 1981).

The fact that children with DCD have a deficient internal representation of movement dynamics has both theoretical and practical importance. First, this finding supports a previously proposed link between this disorder and compromised cerebellar functionality (Bo et al. 2008; Cantin et al. 2007; Ivry 2003; Jongmans et al. 2003; Lundy-Ekman et al. 1991; O’Hare and Khalid 2002; Smits-Engelsman et al. 2001; Smits-Engelsman and Van Galen 1997). A crucial role of cerebellum in control of IT (Bastian et al. 1996, 2000) and in development and storage of the internal models of limb dynamics (Alvarez-Icaza and Boahen 2012; Kawato and Gomi 1992) has been recognized. Also, cerebellar dysfunction causes abnormal patterns of muscle activation (Plament and Hore 1986; Hallett et al. 1991; Hore et al. 1991). Thus our finding of the abnormal muscular
control of IT during catching supports that there is a functional deficit of the cerebellum in children with DCD.

Second, the finding of the impaired internal representation of movement dynamics in children with DCD may offer effective clinical applications. This finding suggests that intervention programs should focus on control of intersegmental dynamics. Also, the quantification of the effectiveness of IT control with the torque analysis, similar to that conducted in the present study, opens perspectives for development of an objective tool that can be used to diagnose DCD, evaluate the progression of the impairment, and assess effectiveness of interventions.

APPENDIX

At each joint, NT, IT, and GT were computed with the use of recorded movement kinematics and parameters of the arm segments with the use of equations presented below for each joint. MT was computed at each joint as MT = NT – IT – GT.

Shoulder Torques

\[
\text{NT}_s = \{I_s + l_s + l_f + m_{fr}r_s^2 + m_{fr}r_f^2 + m_{fr}r_w^2 + m_{fr}r_h^2 + (2m_{fr}l_f + 2m_{fr}r_f)\cos\theta_e + 2m_{fr}r_w\cos\theta_e + 2m_{fr}r_h\cos(\theta_e - \theta_s)\}\dot{\theta}_s
\]

\[
\text{IT}_s = -\{(l_s + l_f + m_{fr}r_s^2 + m_{fr}r_f^2 + m_{fr}r_w^2 + m_{fr}r_h^2 + (2m_{fr}l_f + 2m_{fr}r_f)\cos\theta_e + 2m_{fr}r_w\cos\theta_e + 2m_{fr}r_h\cos(\theta_e - \theta_s)\}\dot{\theta}_s + (I_s + m_{fr}r_s^2 + m_{fr}r_f^2 + m_{fr}r_w^2 + m_{fr}r_h^2 + (2m_{fr}l_f + 2m_{fr}r_f)\cos\theta_e + 2m_{fr}r_w\cos\theta_e + 2m_{fr}r_h\cos(\theta_e - \theta_s))\dot{\theta}_s
\]

\[
\text{GT}_s = -g\{(m_f + m_{fr})l_f\sin\theta_e + (m_f + m_{fr})l_f\sin(\theta_e - \theta_s)\}
\]

Elbow Torques

\[
\text{NT}_e = \{(l_f + l_h + m_{fr}r_f^2 + m_{fr}r_h^2 + 2m_{fr}r_f\cos\theta_e\}\dot{\theta}_h
\]

\[
\text{IT}_e = -\{(l_f + l_h + m_{fr}r_f^2 + m_{fr}r_h^2 + 2m_{fr}r_f\cos\theta_e\}\dot{\theta}_h + (I_f + m_{fr}r_f^2 + m_{fr}r_h^2 + 2m_{fr}r_f\cos\theta_e + 2m_{fr}r_h\cos(\theta_e - \theta_s))\dot{\theta}_h
\]

\[
\text{GT}_e = -g\{(m_f + m_{fr})l_f\sin\theta_e + (m_f + m_{fr})l_f\sin(\theta_e - \theta_s)\}
\]

Wrist Torques

\[
\text{NT}_w = -\{(l_h + m_{fr}r_h^2)\dot{\theta}_w
\]

\[
\text{IT}_w = -\{(l_h + m_{fr}r_h^2 + m_{fr}r_f\cos\theta_e + m_{fr}r_f\cos(\theta_e - \theta_s))\dot{\theta}_w
\]

\[
-\{(l_h + m_{fr}r_h^2 + m_{fr}r_f\cos\theta_e + m_{fr}r_f\cos(\theta_e - \theta_s))\dot{\theta}_w + (m_{fr}l_f\sin\theta_e + m_{fr}\sin(\theta_e - \theta_s))\dot{\theta}_w + (m_{fr}r_h\sin\theta_e + m_{fr}\sin(\theta_e - \theta_s))\dot{\theta}_w
\]

\[
\text{GT}_w = -g\{(m_f + m_{fr})l_f\sin\theta_e + (m_f + m_{fr})l_f\sin(\theta_e - \theta_s)\}
\]

Symbol Definitions

- \( m_u \): mass of the upper arm
- \( m_f \): mass of the forearm
- \( m_{fr} \): mass of the hand
- \( r_s \): length from shoulder to center of mass of the upper arm
- \( r_w \): length from elbow to center of mass of the forearm
- \( r_h \): length from wrist to center of mass of the hand
- \( I_u \): mass moment of inertia of the upper arm
- \( I_f \): mass moment of inertia of the forearm
- \( I_h \): mass moment of inertia of the hand
- \( \theta_s \): shoulder angular displacement
- \( \theta_e \): elbow angular displacement
- \( \theta_w \): wrist angular displacement
- \( \theta_s' \): shoulder angular velocity
- \( \theta_e' \): elbow angular velocity
- \( \theta_w' \): wrist angular velocity
- \( g \): acceleration due to gravity

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DISCLOSURES

The authors have no conflicts of interests.

AUTHOR CONTRIBUTIONS

Author contributions: M.J.A. and E.P.P. conception and design of research; M.J.A. performed experiments; M.J.A., E.P.P., and N.D. analyzed data; M.J.A. and N.D. interpreted results of experiments; M.J.A. prepared figures; M.J.A. and N.D. drafted manuscript; M.J.A. and N.D. edited and revised manuscript; M.J.A., E.P.P., and N.D. approved final version of manuscript.

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