An Unlearned Principle for Controlling Natural Movements

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Zaal, Frank T.J.M., Kristin Daigle, Gerald L. Gottlieb, and E. Thelen. An unlearned principle for controlling natural movements. J. Neurophysiol. 82: 255–259, 1999. Recently, Gottlieb and colleagues discovered a linear relation between elbow and shoulder dynamic torque in natural pointing movements in the sagittal plane. The present study investigates if the process of learning to reach involves discovering this linearity principle. We inspected torque data from four infants who were learning to reach and grab a toy in front of them. In a longitudinal study, we collected data both in the period before and after they performed their first successful reaches. Torque profiles at the shoulder and elbow were typically multipeaked and became more and more biphasic toward the end of the first year of life. Torques at the shoulder and elbow were correlated tightly for movements in the prereaching period as well as for reaches later in the year. Furthermore, slopes of a regression of shoulder dynamic torque on elbow dynamic torque were remarkably constant at a value $-2.5–3.0$. If linear synergy is used by the nervous system to reduce the controlled degrees of freedom, it will act as a strong constraint on the complex of possible coordination patterns for arm movement early in life. Natural reaching movements can capitalize on this constraint because it simplifies the process of learning to reach.

INTRODUCTION

A central issue for understanding human movement is how the excessive degrees of freedom of the neuromotor system are controlled (Bernstein 1967). Even the most common, everyday movement requires coordinating numerous skeletal joints and muscles. Additional complexity comes from the nonlinear interactions between the active and passive forces generated by movements in a linked system. Because the control and coordination of a system of such an anatomic and dynamic complexity would seem to be exceedingly demanding, motor neuroscientists have devoted major efforts to discovering principles by which this problem might be simplified.

Recently, Gottlieb and his colleagues (Gottlieb et al. 1996a,b, 1997) described a simple rule that reduces the degrees of freedom for some multijoint pointing movements. They studied pointing movements in the sagittal plane and noted a proportionality between muscle torques at the shoulder and muscle torques at the elbow

$$\text{torque}_{\text{shoulder}} = K_s \text{torque}_{\text{elbow}}$$

where $K_s$ is the gain constant. Gottlieb et al. (1996a) showed an approximately linear relation between elbow muscle torque and shoulder muscle torque when people are free to choose the path of their hand to point at in front of them. The linearity between elbow and shoulder muscle torque vanishes, however, when the same people are asked to point to the same target but now following a different hand path. Thus it seems that ‘‘natural,’’ or comfortable, movements obey the linearity principle, whereas at the same time people are able to break away from this constraint.

The discovery of a linear relation between shoulder and elbow torque in natural pointing movements led to a number of experiments investigating the effects of speed differences, added weights, and changes in pointing direction (Gottlieb et al. 1996b, 1997). In these studies, Gottlieb and colleagues focused on the transient qualities of the muscle torque and restricted their investigation to the so-called dynamic muscle torques, the portion of muscle torque not concerned with resisting gravity (the latter being static muscle torque). As in the earlier results, there was a linear relation between shoulder dynamic muscle torque and elbow dynamic muscle torque for pointing movements in the sagittal plane. Neither speed manipulations nor added weight changed the parameters of this linear relation, whereas the gain constant, $K_s$, was related directly to the direction of pointing.

That a linear covariance of shoulder torque and elbow torque is seen in natural pointing movements, but not when people point in a less comfortable way, suggests that the linear relation serves movement economy by linking the timing of torque pulses. In the pointing movements studied, torque profiles typically exhibit a biphasic form. A linear relation between two biphasic torque profiles results from a strict temporal coupling of the torque pulses. The slope of the regression of shoulder torque onto elbow torque (i.e., $K_s$) indicates the relative size of the torque pulses at shoulder and elbow. Because deviations from linearity sometimes are observed, this relation cannot be simply a hard-wired biomechanical artifact of a moving linked system. Rather linearity may be a natural organizing principle for decreasing the degrees of freedom at the level of muscle torques, at least for those movement tasks that can be accomplished under such a constraint.

The relation between these muscle torque constraints and regularities at the level of endpoint kinematics is not clear, however. For instance, linear joint torques do not guarantee the straight reaching paths seen in many planar reaches. Indeed, ‘‘comfortable’’ reaches may not be straight at all (Atkeson and Hollerbach 1985). Curiously enough, Gottlieb et al. (1996a) found that more uncomfortable reaches could exhibit straighter handpaths as well as deviations from a linear torque-torque relation.

What, then, is the relation between a linearity constraint at the torque level and regularities at the level of endpoint kinematics? We address this question by looking at the develop-
mental origins of trajectory control. When 3- to 4-mo-old infants first reach out and grab objects, their hand paths are not straight at all but follow a tortuous and indirect route to the target. The corresponding speed profiles are not bell-shaped but show several segments of acceleration and deceleration, giving the movements a jerky quality. During the first year the hand path becomes straighter and smoother, and the high variability of early reaches is reduced (Halverson 1931; Hofsten 1991; Konczak and Dichgans 1997; Thelen et al. 1993, 1996). Infants’ reaches become more and more adult-like, a process that continues at least through the second year of life (Konczak and Dichgans 1997).

Is discovery of the linearity principle one the prerequisites for skilled reaching? If this were true, infants’ reaches would become smoother only as their torques at elbow and shoulder approached a more linear relation. Alternatively, reach smoothness and torque linearity could be unrelated, with the possibility that linearity is a property of comfortable movements whether they are straight, or even whether they indeed are reaching movements. In this case, we would expect that reach straightness and torque linearity would show no correspondence in infants. Indeed, torque linearity may developmentally predate straight reaching or even reaching itself.

To address these issues, we examined kinematic and torque data collected longitudinally from four children during their first year, from weeks 3 to 52, as they were presented with a reachable toy (see Thelen et al. 1993, 1996). When the toy captured infants’ attention, they would make movements of the arms that could be interpreted as attempts at reaching for the attractive object. In the first few months of life, infants were unsuccessful in such efforts. As they grew older, however, they became both faster and more successful in reaching and grabbing the toy. Note that in contrast to the controlled conditions of adult reaching experiments, infants were always free to move when and in any direction and at any speed they chose. This design, and the variability it engendered, allowed a rather strict test of the linearity constraint. If we find torque linearity when movements are not constrained by direction, speed, straightness, or goal, it suggests a fundamental neuromotor organizing principle on which movements are built.

**METHODS**

We followed normally developing infants, three boys and a girl. The longitudinal observations were scheduled weekly from 3 to 30 wk of age, and biweekly until 52 wk (for details, see Thelen et al. 1993, 1996). We presented attractive toys to the infants at midline, shoulder height, and at the distance of their extended arms while they were seated upright with their torsos secured. We collected data in 14-s trials, presenting the toy ~5 s after the start of the trial. Position time data were recorded with a four-camera WATSMART optical-electronic movement analysis system, sampling at 150 Hz, and converted to three-dimensional data using direct linear transformation. Infrared light emitting diodes (IREDS) were placed over each shoulder joint, elbow joint, and wrist joint as well as on the back of each hand of the infant. Because infants could move freely in three-dimensional space, continuous visibility of the IREDS was sometimes a problem. We selected and analyzed portions of trials where spontaneous movements and reaches occurred based on the following protocol: 1) videocoding of each trial by two coders to exclude portions of the trial when the infant was not moving, sucking on fingers, clutching clothing, etc. 2) Determining visibility of the IREDS and using data only when markers were visible through 70% of the segments and when gaps of missing data frames were <333 ms. For the inverse dynamics calculations to be performed, visibility of the IREDS at hand, wrist, elbow, and shoulder was essential. 3) Interpolating obscured data with a linear spline and filtering data based on a 97% cutoff of spectral density profile of each IRED in each coordinate. 4) Rigorous identification of the reach segment itself based on object location, infant’s gaze at the object, and matching visually identified start of the reach movement with velocity minima (see also Corbetta and Thelen 1995; Thelen et al. 1993, 1996). This selection procedure resulted in 22 instances of prereaching movements and 115 reaches (66 from the early reaching period and 49 from the stable reaching period), which could be analyzed for both endpoint kinematics and joint torques. The results presented later are based on these 137 movement segments. No additional criteria were used to discard trials for analysis.

We calculated joint torques at shoulder and elbow using inverse dynamics methods (Schneider and Zernicke 1990). The arm was modeled as three interconnected rigid links (hand, lower arm, upper arm), with frictionless joints at the wrist, elbow, and shoulder. We calculated wrist, elbow, and shoulder angles, as well as their time derivatives, from the 3-D WATSMART data. Shoulder angle was defined as the angle between the vertical passing through the shoulder IRED and the line connecting the IREDS at the shoulder and elbow (180° denotes a vertically oriented upper arm). Elbow angle was defined as the angle between the lines connecting the IREDS at the shoulder and elbow, and the IREDS at the elbow and wrist, respectively (180° denotes a fully extended elbow). Analogously, we computed wrist angles from the positions of the IREDS at the elbow, wrist, and hand. We calculated joint torques using joint angles, their time derivatives, and estimates of mass, center of mass, and moments of inertia based on measured limb segment parameters (Schneider and Zernicke 1992). This method provides torques about axes normal to the moving-local plane through the wrist joints, elbow joints, and shoulder joints (Schneider and Zernicke 1990). Here, we restricted our analyses to the magnitudes of those torques, not considering their directions. At each joint, the net torque (NET) was partitioned into gravity (GRA), motion-dependent (MDT), and generalized muscle torque (MUS) components (for more details and examples of the use of this method applied to infant limb movement, for instance, see Konczak and Thelen 1994; Konczak et al. 1997a; Schneider et al. 1990). The torque due to muscle alone is thus MUS = NET − MDT − GRA. Here we are only interested in the dynamic portion of muscle torque: the quantity NET − MDT (cf. Gottlieb et al. 1996b, 1997). Finally, we normalized torques for body weight, to be able to compare results among different ages.

**RESULTS**

Figures 1–3 illustrate typical infant movements in the prereach, early reach and stable reach periods, in this example at the age of 19, 29, and 42 wk, respectively (criteria for determining these developmental epochs are reported in Thelen et al. 1996). The four infants first consistently touched or grasped the toy at 12, 15, 20, and 20 wk (the reaches presented in Figs. 1–3 are from the same infant, who first touched the toy at 20 wk). Before that time, they visually fixated the toy, and often moved their arms, but were not successful in touching or grasping it, as suggested by the rather random motion shown in Fig. 1A. Early reaches, typified by Fig. 2A, were controlled poorly and were extremely variable, as indicated by an index of hand path straightness, the number of speed accelerations and decelerations, and the average and contact speed of the hand (Thelen et al. 1993, 1996). Coordination between the rotations of the shoulder and elbow was also poor and variable, as shown in Figs. 1C and 2C, reflecting the diverse starting positions of their reaches and the tortuous hand paths. At ~30–34 wk of
age, reach control stabilized noticeably, with more straight and smooth reaches (Fig. 3) and less variable speeds, although even at 1 yr, infants were not reaching in a fully adult manner.

Despite infants’ poor control of their hand paths and joint excursions, they adhered strictly to the principle of linear synergy throughout the first year, both in movements before they learned to successfully reach and afterward. Figure 4 shows distributions of the correlation coefficients ($r$) and of the slopes ($K_d$) of a linear regression of shoulder torque onto elbow torque for each inspected movement. The results are presented separately for the early prereaching period, the highly variable postreaching onset periods, and the later, more stable period (Thelen et al. 1996). Correlation coefficients were uniformly close to unity, showing that the increases and decreases of force at the two joints were nearly perfectly in synchrony. Moreover, for these reaches at midline and shoulder height, $K_d$ remained near 2.5–3.0 [2.68 ± 0.70 (mean ± SD) in the prereaching period; 2.45 ± 0.41 in the early period; 2.83 ± 0.40 in the stable period). Even more remarkable was that infants appeared to retain this torque invariance even in their nonreaching movements. The synchrony between forces at shoulder and elbow was nearly perfect, and the slope approximated that of the reaching movements. The examples from the prereaching period (Fig. 1), the early reaching period (Fig. 2), and the stable reaching period (Fig. 3), all from the same infant, illustrate the dramatic contrast between the variability at the level of hand kinematics and the dynamic torque-torque stability.

**DISCUSSION**

These results suggest that the principle of linear synergy is a fundamental property of the human neuromotor system from early in life and is likely not learned as a means to constrain the kinematics of the hand into the forms seen in adult reaching. Clearly, the principle is not responsible for the straightness of the
hand path nor for the unimodal bell-shaped speed profile. Thus following the principle of linear synergy does not simply lead to the kinematics we well know in adult reaching. Rather, successful reaching for a target must be sculpted into the temporal structure of the torque patterns from this preference of the system to apportion dynamic torque proportionately and synchronously between shoulder and elbow. Even as the hand wandered from the path to the toy, or as infants moved in a seemingly non–goal-directed fashion, the coordination was maintained. This held across the transition from prereaching to reaching despite evidence that infants recruited different sets of muscles to move to the same place in space (Spencer and Thelen 1996). The principle acts as a constraint in the high-dimensional space of kinematic and dynamic possibilities, thereby reducing the degrees of freedom of the problem of learning to control the arm for purposeful activity (Bernstein 1967).

Although these results are based on a relatively small population of four infants, the time series data are remarkably similar to that of others. For example, Fig. 2 of Konczak et al. (1997a) shows an example of elbow and shoulder torques in a young infant. They are multiphasic but well synchronized and would probably show a high degree of colinearity between joints were they plotted as we have in Figs. 1–3. The joint torques of the older infants shown in that figure appear to be less linear but this is because the gravitational component was included.

The invariance of the slope in infants’ reaching movements throughout their first year may be explained by our always presenting the toy to the same place at midline. Although the location of the toy is certainly an interesting variable to be considered in future research, the location of the target cannot be a factor for nonreaching movements, which also showed a strong tendency to have a torque-torque slope close to the mean of 2.6. More likely, while infants can move to many areas in their reaching space, limb anatomic and energetic considerations make certain configurations more attractive than others. Indeed, during the prereaching period, infants’ hands were most likely to be in front of them or between the midline and shoulder at no higher than the chest for a majority of the time. Movements at the extremes of the reaching space were less frequently seen (Spencer and Thelen 1996). Interestingly, Gottlieb et al. (1997) computed $K_d$ values for various (adult) reaching movements taken from their earlier studies, in which speed and load, among other things, were manipulated (see Fig. 11 in Gottlieb et al. 1997). In their center-out task and center-crossing task, $K_d$ was related to movement direction but $K_d$ was $\sim 2.5$ for all other movements. These latter movements were all directed at targets located in front of and above the initial position of the hand as were the infant reaches presented here.

With the linear synergy principle acting as a constraint on the complex of possible coordination patterns, the infant neuromotor system is configured to make the acquisition of reaching easier. Thelen et al. (1993) suggested that infants shifted from spontaneous movements to successful reaching by working on the force dynamics to initially get the hand in the ‘‘ball park’’ of the visually fixated target. Because each of the four infants differed in the predominant speed of prereaching movements and in the amplitudes of muscle torque generated, they needed to individually discover torque levels to approach the object at an appropriate speed. The present results indicate that shoulder–elbow torque proportion and synchrony is maintained in this scaling. Movement distance and speed may be modulated by scalar changes in the muscle activation that generates torques around the joints. Relatively subtle adjustments in the relative apportionment and timing of joint torque, learned by trial and error, may be sufficient to specify trajectory direction. Natural reaching movements capitalize on the intrinsic coupled dynamics of the arm.

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