EXERTION LEVEL AND THE INTENSITY OF ASSOCIATED MOVEMENTS

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Involuntary contractions of uninvolved muscles have been observed and studied in a variety of movements. While there are slight variations in context, this behaviour has been referred to as associated movements (Fog and Fog 1963), motor overflow (Yensen 1965), synkinesis (Cambier and Dehen 1977), mirror movements (Green 1967) and motor irradiation (Cernacek 1961).

During unimanual acts, a frequently observed pattern is for involuntary movements to occur in the contralateral homologous or mirror-image muscles. Although less common, several studies have reported co-contraction of the contralateral heterologous muscles (*i.e.* contralateral antagonist), at least on some trials. The proportion of the homologous to heterologous associated movements apparently varies with age (Fog and Fog 1963, Missiuro 1963). While these studies conflict with respect to which movement pattern increases with age, they do reinforce the notion that not all associated movements involve mirror-image muscles. For this reason studies of associated movements should be designed to detect both mirror and non-mirror movements.

A number of studies have noted that associated movements are more pronounced and more frequent if the subject is asked to exert more force (Cernacek 1961, Fog and Fog 1963, Podivinsky 1964, Stern *et al.* 1976). Investigators have suggested that there is a minimal force necessary to elicit associated movements (Cernacek 1961, Podivinsky 1964). In spite of this, the relationship between the force of the intended movement and the magnitude of the associated movement has not been systematically studied.

The most common measure of associated movements has been to record the frequency with which they are observed across repeated trials (Cernacek 1961, Fog and Fog 1963, Abercrombie *et al.* 1964, Podivinsky 1964, Stern *et al.* 1976). If the intensity of the active contraction influences the manifestation of associated movements, and if the relative exertion level of the active limb is not controlled, then the frequency count and any subjective intensity rating could be misleading. Notably, this type of confounding would influence the assessment of age or sex differences, since both variables influence a subject's absolute strength. Furthermore, many of the clinical populations that exhibit excessive associated movements are also characterized by having only crude control over force, typically over-exerting; consequently any tendency for associated movements to occur would be exacerbated (Cohen *et al.* 1967, Szatmari and Taylor 1984).

In many studies involuntary associated movements have been observed more

Developmental Medicine & Child Neurology, 1986, 28, 205–212

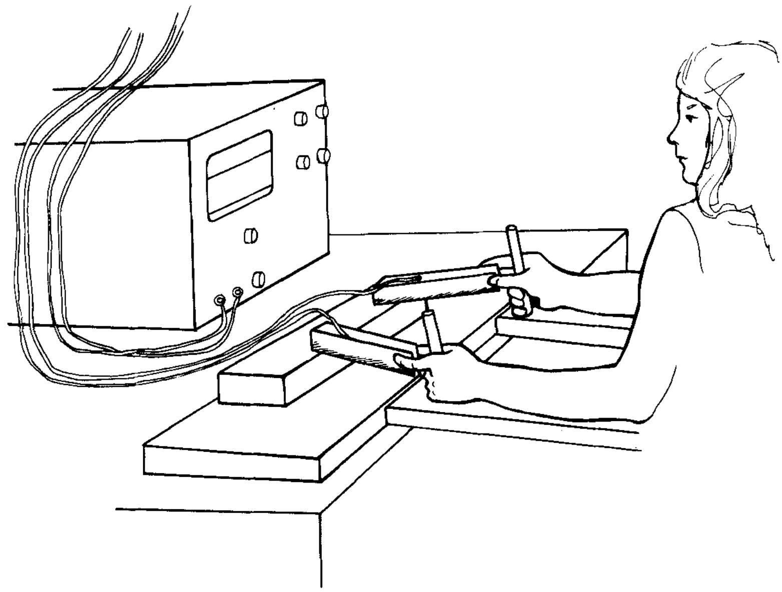

Fig. 1. Apparatus for assessment of associated movements.

frequently when the non-preferred left hand performs the intended act and the associated movements are assessed in the right hand (Davis 1942, Cohen *et al.* 1967, Touwen and Prechtl 1970, Stern *et al.* 1976, Wolff *et al.* 1983). Similar to the assessment of age and sex differences, the comparison of the right and left hands may have been biased if the relative intensity of the active contraction was not regulated. If a standard task were used and the left hand were weaker, it would have performed an active contraction representing a greater percentage of its maximum (Spreen and Gaddes 1969). Hence it is conceivable that the observation of more associated movements when the left hand is active may be attributed, at least partially, to differential exertion.

The order of hand use introduces an additional complication when assessing potential lateral asymmetries in motor functions. Hutton (1985) has reported post-contraction increases in motor neuron excitability lasting up to two minutes. Therefore it is conceivable that a fixed order of testing would result in the appearance of more pronounced associated movements in the limb previously engaged in the volitional contraction. While counterbalancing for the order of hand use would provide protection against this effect, it may increase the variance associated with a given hand when the data are pooled across orders.

The purpose of the present study was threefold: (1) to assess the relationship between the force of the active hand contraction and the magnitude of the observed associated movements; (2) to determine whether lateral asymmetries exist in the magnitude of associated movements when the force of the active limb contraction is controlled; and (3) to determine whether the order of hand use influences the magnitude of the associated movements.

Method

Forty-two children (19 male, 23 female) participated in the study. Their ages ranged from 7 years 6 months to 8 years 11 months (male mean 94·9 months, SD 4·67; female mean 96·8 months, SD 3·41). Only children who wrote with their right hand were tested. Children identified by the school district as having learning disabilities and/or atypical motor function were excluded.

The apparatus used was a modified version of the clip-pinching task of Fog and Fog (1963) (Fig. 1). Two parallel steel bars were attached to a platform, which was secured to a desk. Strain gauges were mounted on the inner surface of the lateral bar for each hand. The output of the strain gauges was amplified by a Beckman R611 polygraph, displayed on an oscilloscope, and stored subsequently in an instrumentation tape-recorder (Hewlett-Packard model 3960). The oscilloscope displayed a horizontal line which rose in proportion to the force of the contraction of the active hand.

Each child was seated on an adjustable stool facing the apparatus. The forearms were positioned and secured with velcro straps to the arm-rests. The child was instructed to place the thumb and index finger of each hand on the outside of the squeeze bars at a standardized location. The thumbs were positioned so that they were in alignment with the radial side of the forearm, restricting the squeezing movement to flexion of the index finger. The rest of the fingers were wrapped around wooden dowels projecting from the horizontal armrests.

Children were randomly assigned to perform first with their right hand (R/L order) or left hand (L/R order). They were instructed to squeeze the bars with the performing hand to raise the line on the oscilloscope as high as they could by squeezing as hard as possible. The peak value was then used as the child's maximal volitional force (MVF). They were instructed to keep the other thumb/finger motionless in the starting position during all trials, *i.e.* in contact with the bars. They were then asked to squeeze the bars to 25, 50, 75 and 100 per cent of their MVF. Horizontal color-coded marks on the oscilloscope indicated to the child how high to raise the line to achieve the desired force level. Three trials were performed at each level, beginning with 25 per cent of MVF and progressing to 100 per cent. An individual trial lasted six seconds, giving ample time for the children to attain the desired force. Trials were separated by a 10-second rest interval. Five minutes after completing the required series of contractions with one hand, the rôle of the hands (active/passive) was reversed.

Analysis

The force output recorded from the contralateral (passive) hand was used to represent the magnitude of associated movement. The analogue recordings from the tape were converted to digital values by a microcomputer sampling every 4msecs. The onset of force in each trial triggered an eight-second sampling algorithm which computed the average force output of each hand during consecutive time-intervals or bins of 0·4, 1·1, 1·1, 1·1, 1·1, 1·1, 1·1 and 1·0 seconds. Before statistical analysis, corrections were made for differences in D/C offset, signal amplication and the sensitivities of the two strain gauges.

The data obtained in the first bin were excluded from the analysis since it contained adjustments associated with attaining the desired level. To ensure that co-contraction values were associated with a given exertion level, at least 80 per cent of the desired active hand-force had to be maintained for a minimum of three consecutive sampling bins (*i.e.* 3·3 seconds). Trials failing to meet this criterion were excluded from the analysis. Further, for each trial, only bins meeting the performance criterion were analyzed. The 'passive hand' associated movement was defined as the highest value of the bins qualifying in that trial. This value was viewed as more appropriate than the overall average for the following reasons. There was trial to trial variation in the number of bins meeting the performance criterion and the qualifying bins may have occurred early or late in the trial. Since we had subjectively observed the intensity of the co-contraction to increase as a function of the duration of the active contraction, an average value for overflow would not be representative, underestimating on trials of short duration or where the peak associated movement occurred early in the six-second period.

The frequency of heterologous movements (extension of the thumb and/or index finger) was noted. Since these movements were not quantified, the trials in which they occurred were excluded from the statistical analysis.

Results

Table I presents means and standard deviations for the magnitude of associated movements by sex, order, hand and active hand force level. In all subgroups the standard deviation increased with intensity

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TABLE I

Means and standard deviations for magnitude of associated movements by sex, order, hand and active hand-force level

	Male		*Female*	
% MVF	*RL*	*LR*	*RL*	*LR*
Cell means				
R25	83·614	29·481	2·208	20·404
R50	122·931	68·878	138·998	98·586
R75	443·402	377·247	500·854	428·458
R100	1113·256	1126·141	1502·558	1095·308
L25	6·844	30·918	81·744	15·351
L50	22·070	99·873	69·796	201·402
L75	200·128	436·320	374·089	329·494
L100	268·512	1324·643	900:597	838·980
Standard deviations				
R25	83·393	53·760	26·279	64·897
R50	162·074	133·110	164·656	203·509
R75	445·393	485·287	597·192	649·831
R100	1381·547	835·642	1051·940	839·749
L25	57·143	57·978	253·824	51·411
L50	82·194	120·224	176·622	442·177
L75	317·798	481·603	603·316	539·976
L100	452·458	1069·160	858·381	770·535

TABLE II

Number of heterologous movements of 'passive hand'

	% MVF				
	25	*50*	*75*	*100*	*Total*
Active hand					
Right	0	1	7	6	14
Left	1	2	10	27	40
Total	1	3	17	33	54

of the active hand force. This effect can be attributed, at least in part, to the restricted freedom to vary at lower levels of active hand force, where the magnitude of associated movements was close to zero. To counteract the impact of unequal variances a logarithmic transformation of the values was used in the analysis of variance (sex×order×hand×active hand force level). Box's test for equality of variances confirmed that there was homogeneity of variance across force levels for the transformed values.

There was a highly significant main effect due to active hand force level ($F[3,114]=146 \cdot 9$, $p<0 \cdot 0001$). As can be seen in Figure 2, the intensity of the associated movements increased only slightly between 25 and 50 per cent MVF, but increased dramatically in intensity at 75 and 100 per cent MVF. When expressed as a percentage of the active hand's absolute force level, the associated movement ranged from 13·3 to 62·7 per cent.

The main effect for hand was significant ($F[1,38]=5 \cdot 06$, $p<0 \cdot 03$), signifying more intense associated movements in the right hand when the left hand was active than the converse. The hand by level interaction was not significant.

There was no significant main effect of order. However, a hand by order interaction was evident ($F[1,38]=7 \cdot 59$, $p<0 \cdot 009$). As Figure 3 illustrates, hand differences existed in the R/L order of performance but not in the L/R order. There was no main effect or interaction involving sex.

Extension of the finger/thumb (heterologous movement) was observed in the 'passive hand' during flexion of the active hand on 17 per cent of the qualifying trials. The pattern of occurrence of heterologous movements was similar to the magnitude of the more prevalent simultaneous co-flexion (see Table II). The number of heterologous movements and the magnitude of the co-flexion increased as the force of the active hand increased, and the effects were more pronounced when the left hand was active.

A second 2×2×2×4 (sex×order×

hand×active hand force level) analysis of variance with repeated measures was performed on the intensity of associated movements, expressed as a percentage of the active hand maximal volitional force (100 per cent MVF). These computations were carried out to control for the possibility that the magnitude of the co-contraction observed in one hand might be a function of the absolute force of the other hand. Since this analysis revealed only significant effects on the same factors as the analysis of the absolute values of the associated movements, it will not be discussed further.

Discussion

The primary finding of the current study is the delineation of a relationship between the force exerted by the active limb and the force of associated movements in the contralateral hand. Although a number of investigators had noted the likelihood of such a relationship, none had studied it systematically (Davis 1942, Cernacek 1961, Fog and Fog 1963, Abercrombie *et al.* 1964, Stern *et al.* 1976). Most previous investigations of associated movements obtained only subjective measures. In contrast, this study quantitatively assessed the magnitude of the associated movements while the children performed active contractions at fixed percentages of their own maximal volitional force level.

Wolff *et al.* (1983) have argued that associated movements, as detected by noting the frequency of involuntary simultaneous movements, should be distinguished from random motor irradiation observed during extreme exertion. The results of this investigation indicate that when the involvement of postural synergies is reduced by restricting the active contraction to index-finger flexor, involuntary associated movements are not random and occur predominantly in the mirror-image muscles of the contralateral hand. At this point there are insufficient experimental data to determine if the irradiation due to exertion and associated movements are mediated by the same mechanism. However, it is evident that the exertion level of the desired movement influences the occurrence of associated movements. The data clearly indicate that

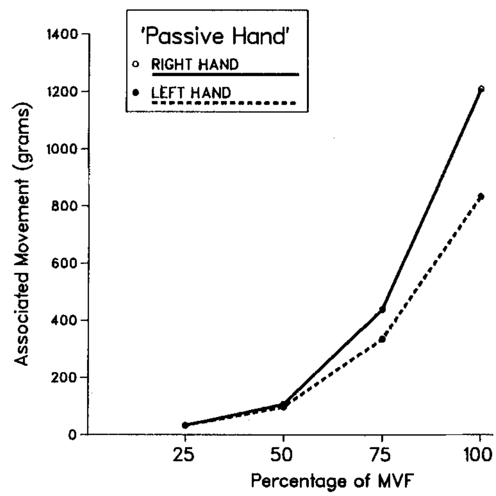

Fig. 2. Associated movements by hand at various levels of maximal volitional force (MVF).

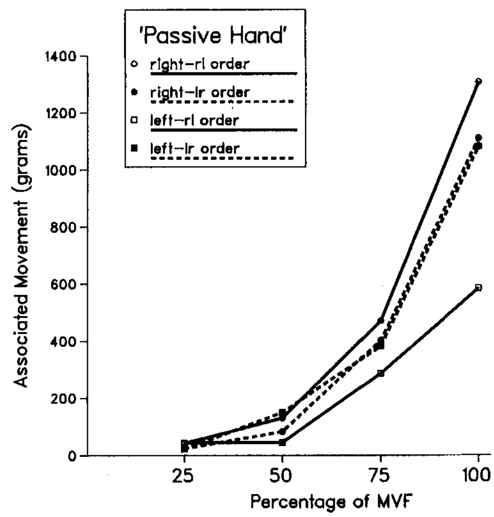

Fig. 3. Associated movements by hand and order at various levels of maximal volitional force (MVF).

as the intensity of the contraction in the active limb increases above 50 per cent MVF, the intensity of the associated movements increase. Further, since these associated movements reached magnitudes of up to 62·7 per cent of the active hand force, the effect can be substantial.

Since the children performed the active hand contractions in a fixed ascending order of intensity, it is conceivable that some of the observed increase in associated movements were due to a cumulative fatigue factor. However, since only trials in which the criterion force was met were included in the analysis, fatigue could not have been an overwhelming factor. Therefore, because of this interrelationship between exertion level and the manifestation of associated movements, it is critical to systematically compare subjects performing contractions that are equivalent proportions of their individual maximum exertion level. This would be especially important in the evaluation of developmental trends or sex differences, where systematic differences in strength are expected.

A frequent observation has been to detect more associated movements in the dominant right hand when the non-dominant left hand is active than the converse (Welch 1898, Davis 1942, Cohen *et al.* 1967, Touwen and Prechtl 1970, Stern *et al.* 1976). However, those studies did not control the active hand force level or used a common absolute force level with both hands. This study controlled for the relative strength of the hands and still found evidence of a similar lateral asymmetry. Associated movements were more intense in the right hand (left hand active) than the converse.

At least three non-independent factors may contribute to the lateral asymmetry in the intensity of associated movements. First, Semmes (1968) contends that sensorimotor functions are represented differently in the right and left cerebral hemispheres. In the left hemisphere, which controls voluntary activity of the right hand, these functions are focally represented. In the right hemisphere, which is involved in controlling the left hand, these functions are more diffusely represented. Thus one might infer that left-hemispheric activity resulting in right-hand movements would be more localized, decreasing the potential for motor irradiation. In contrast, when the left hand is used the neural activity would spread more diffusely. Indirect support for this position has been given by Halsey *et al.* (1979), who reported more prominent increase in Rolandic cerebral blood-flow during left-hand movements than right, indicative of more neuronal involvement.

Second, Kimura and Archibald (1974) have argued that the left hemisphere is differentially involved in the motor control of both hands. Thus, when the left hand is active, neuronal activity would occur in both right and left hemispheres, increasing the potential spread to motor areas in the left hemisphere controlling the right hand. However, right-hand movements would involve a circumscribed area restricted to the left hemisphere, and primarily affect contralateral pathways to the right hand.

Third, the differential use of the preferred right hand may lead to the development of more refined patterns of neuronal activity which are less diffuse. This implies that left-hand movements, typically being less efficient, would involve a more diffuse network of cortical neurons, which conceivably leads to greater associated movements (for a more detailed discussion of these hypotheses the reader is referred to the chapter by Todor and Lazarus 1985).

In this study the order of hand use significantly influenced the observance of a hand difference. However, since there was a significant hand difference when the data of the two orders were combined, there appears to be both an order effect and a lateral asymmetry in the magnitude of associated movements. Apparently the order effect is sufficiently pronounced to obscure hand differences in the L/R order. Several explanations have been entertained to account for the apparent elevation in associated movements after the 'passive hand' has been active. First, prior contraction may have increased the subsequent excitability of the motor neurons and muscles involved. Although such an effect has been clearly demonstrated, its influence has not been found to persist more than two minutes (Hutton 1985). In the present study a five-minute period intervened between the active contraction of a given hand and its subsequent involvement as the 'passive hand'. A second potential causal factor may be the priming of a given cerebral hemisphere, in a manner similar to that proposed by Kinsbourne (1970). In this case prior contraction by a given hand may leave the controlling contralateral hemisphere differentially susceptible to activation, leading to enhanced associated movements. While these explanations are speculative, the data are sufficiently robust to argue for consideration of order effects in subsequent studies of lateral asymmetries in associated movements.

The observation of heterologous movements in the 'passive hand' on 17 per cent of the trials suggests that this behavior was not due to momentary lapses in attention to the task, but rather was an involuntary co-contraction. Further, the frequency of this behavior varied as a function of active hand and exertion in a pattern similar to the homologous co-flexion. Therefore these co-contractions of the contralateral antagonist muscles appear to be an alternative form of a common phenomenon.

Missiuro (1963) has reported a potentially related phenomenon. Associated movements accompanying elbow flexion were most prevalent in the contralateral extensors of three- to six-year-old children, while among older children the primary effect was seen in the contralateral flexors. Missiuro suggested that this pattern exists because for the younger group 'the corticospinal control of movement is not yet well established and they show a preponderance of the excitatory processes over those of inhibition, together with a tendency of the reflex responses to generalizations' (pp. 35–36). This is interpreted to imply that cortical inhibition is weaker or less functional in the younger children, resulting in an involuntary activation of a spinal crossed flexion-extension reflex. Further, the spread to homologous muscles in the opposite limb may not have occurred to any great extent in the younger children because of later maturation of structures in the cerebral cortex (*i.e.* corpus callosum) that might be mediating this spread (Dennis 1976, Salamy 1978). If such a developmental trend exists, then the systematic but less frequent occurrence of heterologous movements might reflect an incomplete transition.

In contrast to Missiuro's observations of the intensity of heterologous associated movements, Fog and Fog (1963) found the frequency of heterologous movements to be greater in older children. However, methodological differences might account for the apparent discrepancy (*i.e.* frequency counting *vs.* EMG recording; different muscle groups used; task-defined force required, so subjects varied in the percentage of their individual maximal force). While the developmental pattern remains unresolved, it is apparent that true 'mirror movements' only represent the dominant form of involuntary co-contractions. This position is corroborated by Hellebrandt and Waterland (1962), who noted heterologous movements in adults. Additionally, while Wolff *et al.* (1983) found mirror movements to decrease with age, they observed some evidence of a corresponding increase in more diffuse associated movements. Consequently efforts to understand the nature of associated movements and their interactions with developmental processes must consider the pattern or patterns of their manifestation.

Accepted for publication 29th July 1985.

Acknowledgements
The authors are grateful for the co-operation of Dr. Ruth Moormon, Carol Cross and the staff and students of the Willow Run School District, Ypsilanti, Michigan.

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SUMMARY
Associated movements in the contralateral limbs were measured quantitatively for 42 seven- to eight-year-old children who wrote with the right hand. Associated movements of the contralateral homologous muscles systematically increased as a function of the intensity of contraction of the active hand. The associated movements were more intense when the left hand was active. The order of hand use markedly affected the lateral asymmetry, indicating that the right and left hands were affected differentially by previous activity. Associated movements of the contralateral antagonist muscles were also observed, and their frequency varied as a function of active hand and exertion level.

RÉSUMÉ
Les mouvements associés des membres contro-latéraux ont été étudiés quantitativement chez 42 enfants âgés de sept ou huit ans écrivant avec la main droite. Les mouvements associés des muscles controlatéraux homologues augmentaient systématiquement en fonction de l'intensité de la contraction dans la main active. Les mouvements associés étaient plus intenses lorsque la main gauche était active. L'ordre d'utilisation de la

main affectait de façon marquée l'asymétrie latérale, indiquant que les mains droite et gauche étaient affectées différemment par l'activité antérieure. Les mouvements associés des muscles antagonistes contralatéraux ont été aussi observés et leur fréquence variait en fonction de la main active et du niveau d'activité.

ZUSAMMENFASSUNG

Bei 42 sieben- bis achtjährigen Kindern, die mit der rechten Hand schrieben, wurden die assoziierten Bewegungen der kontralateralen Seite quantitativ gemessen. Die assoziierten Bewegungen der kontralateralen homologen Muskeln nahmen systematisch als eine Funktion des Kontraktionsgrades der aktiven Hand zu. Die assoziierten Bewegungen waren intensiver, wenn die linke Hand aktiv war. Die Reihenfolge des Handgebrauchs beeinflußte deutlich die laterale Asymmetrie, was anzeigt, daß die rechte und linke Hand durch vorausgegangene Aktivität unterschiedlich beeinflußt wurden. Es wurden auch assoziierte Bewegungen der kontralateralen Antagonisten beobachtet, ihre Frequenz wechselte als eine Funktion der aktiven Hand und des Anspannungsgrades.

RESUMEN

Si midieron los movimientos asociados de las extremidades contralaterales y de forma cuantitativa en 42 niños de siete a ocho años de edad, que escribian con la mano derecha. Los movimientos asociados de los músculos homologos contralaterales aumentaban sistemáticamente en función de la intensidad de la contracción de la mano activa. Los movimientos asociados eran más intensos cuando la mano izquierda era la activa. El orden en el uso de la mano afectaba marcadamente la asimetría lateral, indicando que las manos derecha e izquierda se afectaban diferentemente sugún la actividad previa. También se observaron movimientos asociados de los músculos antagonistas contralaterales i su frecuencia variaba en función de la mano activa y el nivel de esfuerzo.

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