

Kinaesthetic judgements and refinement of striking action

Andrew B Roberts BSc(Hons), Graduate student;
Mark Mon-Williams* PhD, Lecturer in Cognitive Neuroscience;
James R Tresilian PhD, Senior Lecturer in Motor Control;
Robin Burgess-Limerick PhD, Lecturer in Clinical Biomechanics, School of Psychology, University of St Andrews, St Andrews, Fife KY16 9JU, Scotland.

*Correspondence to second author at address above.
E-mail: mon@st-andrews.ac.uk

Little is known about the developmental course of striking action. This cross-sectional study explored the refinement of striking in 28 children aged between 4 and 12 years and investigated how well they could use kinaesthesia to gauge the length of an unseen bat. The kinematic data (including smoothness of movement) showed quantitative differences between the age groups. In contrast, no differences were found in the children's ability to judge the length of the unseen bat: within three strikes all of the children had made a clean hit, indicating that they had successfully judged bat length. The children then appeared to memorize the bat with which they had accurately hit the target and made: (1) minimal errors when using this bat in later trials and (2) predictable errors when using two other bats of different sizes. The results show that the striking action becomes optimized over childhood, with smoothness of movement providing an index of this refinement. The findings also suggest that young children have a higher level of kinaesthetic sensitivity than has been assumed previously on the basis of static limb positioning tasks. The results suggest that the striking task used in this study might be a useful tool for investigating the development of movement skills in children with developmental disorders.

The task of striking requires hitting a moving or stationary target (generally a ball) with either the hand or a hand-held bat or racquet. It is known that children as young as 3 years can successfully strike a stationary ball with a bat and, in certain cultures (e.g. the USA and the UK), it is expected that children will enter school at age 5 years with the ability to carry out such a 'basic' strike action (Keogh and Sugden 1985). The purpose of this paper is to dissect some of the fundamental components of the strike action. This paper will focus on: (1) the use of kinaesthesia in carrying out a striking task and (2) the extent to which the striking action differs in children of different ages.

Various terms are used to describe the perception that arises from limb position information but we will restrict ourselves to using the term kinaesthesia. Several studies have claimed to examine children's ability to make 'kinaesthetic judgements' (e.g. Bairstow and Laszlo 1981; Laszlo and Bairstow 1983, 1985, 1988; Doyle et al. 1986; Lord and Hulme 1987; Elliot et al. 1988; von Hofsten and Rosblad 1988; Hoare and Larkin 1991). It may be argued, however, many of these supposed tests of kinaesthesia are flawed: for instance, many tests require a relational judgement ('which hand is higher'); impose a memory load (e.g. movement reproduction); or test the egocentric mapping of kinaesthetic cues rather than kinaesthetic sensitivity per se (see Wann 1991, Smyth and Mason 1998, Mon-Williams et al. 1999). Controversy also exists over the level of 'kinaesthetic sensitivity' in young children (cf. Bairstow and Laszlo 1981; Laszlo and Bairstow 1983, 1985, 1988; Doyle et al. 1986; Lord and Hulme 1987; Elliott et al. 1988; von Hofsten and Rosblad 1988; Hoare and Larkin 1991; Smyth and Mason 1998). Surprisingly few (if any) studies have explored the manner in which children use kinaesthetic information for future planning in a dynamic context (e.g. in a striking task). A number of everyday dynamic situations require a mapping between vision and kinaesthetically derived information. For example, it is possible to fixate the ball or the racquet when playing tennis, but not both. It is likely that the ball is fixated and information regarding the dimension and position of the racquet is determined from kinaesthesia. This raises the issue of the extent to which it is possible to determine the dimensions of a hand-held object from kinaesthesia. It is known that adults can judge the length of an unseen rod with a high degree of accuracy (Turvey 1996) and several studies have found that adults use a single valued function of the moment of inertia (how much an object resists rotation) to determine a hand-held object's length (Burton et al. 1990; Barac-Cikoja and Turvey 1991; Burton and Turvey 1991; Turvey et al. 1992). Unfortunately, the extent to which children are able to use kinaesthetic information to judge the dimensions of an unseen hand-held object has not been explored.

The action of ball hitting is a good example of kinaesthesia in a dynamic context. One major advantage of exploring kinaesthesia through ball hitting is that it directly maps on to the types of diagnostic tests (such as the Movement Assessment Battery for Children—MABC, Henderson and Sugden 1992) used for exploring childhood movement problems. The use of a ball-hitting task thus has potential diagnostic value as it allows for a detailed investigation of why a child fails to complete a number of everyday complex tasks (see Wann et al. 1998). This sentiment was expressed to us by an anonymous reviewer of this paper who wrote 'there

is a considerable void between tests of impairment such as the MABC battery and current tests of function/process such as visual proprioceptive mapping. A ball-hitting paradigm has the potential to fill that void by using dynamic tasks with varying kinaesthetic demands and precise limb recording' (personal communication).

Another advantage of the ball-hitting task is that it allows the action to be dissected and measured. We were interested in the extent to which quantitative differences in striking could be observed in groups of children of different ages. Wann and Jones (1986) have proposed that movement refinement can be considered as a process whereby a primary movement goal is accomplished with increasing reference to some secondary criteria. Nelson (1983) suggested that movements may be refined by optimizing the trajectories relative to a variety of plausible criteria such as movement time, distance travelled, exerted force, movement effort, energy, and smoothness. Optimization refers to finding the movement pattern that either maximizes or minimizes the criterion chosen. One particularly useful criterion in documenting skilled versus novice performance is the minimization of jerk (e.g. Hogan 1984, Flash and Hogan 1985); this has been found to be useful for describing the trajectories of human arm movements during reaching, pointing, and drawing tasks (Flash and Hogan 1985, Flash 1987, Wann et al. 1989). Such approaches promise new insights into the refinement of movement in both typical and atypical childhood development (Wann 1987). For example, Wann and Jones (1986) found that they could identify children with control difficulties by analysing the smoothness of their handwriting.

Although many studies have used advanced research techniques to explore the dynamics of adult striking, we are aware of no such studies in children. Indeed, even the basic documentation of how strike action progresses with age is somewhat sparse (see Keogh and Sugden 1985, p109). Therefore, we used a simple striking task to assess the ability of children to judge the length of an unseen bat and to address the issue of skill refinement.

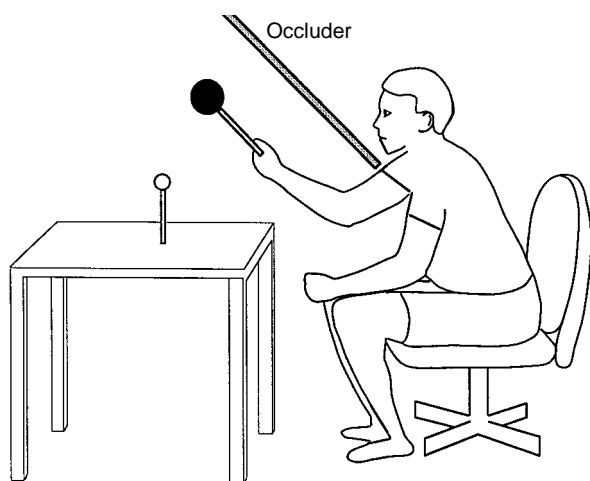


Figure 1: Schematic of experimental apparatus. Children were sat in a chair and banded one of three bats. An occluder ensured that children could not see bat but could see a stationary ball which they were asked to hit.

Method

PARTICIPANTS

Twenty-eight children aged between 4 and 12 years participated in the experiment. All of the participants were recruited from a university vacation care programme. Informed parental consent was obtained for all children and the experiments received ethical approval from the university. All 28 children were screened using the MABC (Henderson and Sugden 1992), each child performing at a level normal for their age (> upper 25th centile). All of the children preferred to use their right hand for handwriting and throwing a ball. The children were placed in groups according to the age bands specified in the MABC — age band 1: school children (four boys, three girls) aged from 4 to <7 years (mean 5.4 years); age band 2: school children (four girls, three boys) aged between 7 and <9 years (mean 7.9 years); age band 3: school children (four boys, three girls) aged between 9 and <11 years (mean 9.7 years); age band 4: school children (five girls, two boys) aged between 11 and <13 years (mean 11.3 years).

APPARATUS

Infrared emitting diodes (IREDs) were used in conjunction with a three-dimensional camera system (Optotrak, Northern Digital, Ontario, Canada) to obtain instantaneous positional information about the centre point of the bat with respect to the centre point of the ball. The IRED positions were sampled at a rate of 200 Hz and used to plot the kinematics of the bat and the spatial accuracy of the strike.

The balls used were plastic lightweight practice golf balls (diameter 4 cm). Custom-made bats were constructed from a metal rod (diameter 9 mm) which had an attached head with a flat, circular face (diameter 80 mm, thickness 16 mm). Each bat had a standard soft handle (diameter 30 mm, thickness 120 mm) around the bottom of the rod to ensure the participant had both an adequate and comfortable grip. Three bats of different lengths (300, 350, and 400 mm) were used for the experiment. The task for the children was to strike the

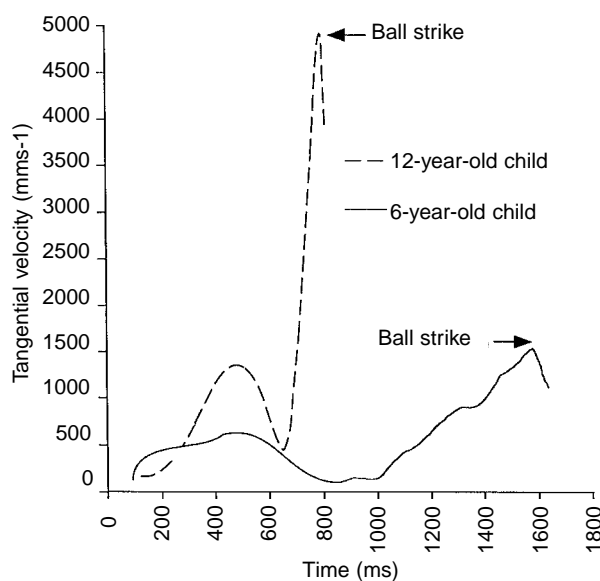


Figure 2: Representative plots (randomly selected) showing velocity profile for a 12-year-old and 6-year-old child.

ball from a tee, aiming to hit a target positioned 3 metres away. The average arm length of the children was 47 cm for age band 1, 53 cm for age band 2, 60 cm for age band 3, and 65 cm for age band 4. The children were seated with their right acromion process at an approximate distance of 30 cm from the ball in the coronal plane and 65 cm in the sagittal plane when facing straight ahead (primary position). This arrangement meant that it was possible for the children either to overshoot or undershoot the centre of the ball in the horizontal plane by approximately 20 cm when swinging the bat (assuming comfortable arm postures). The ball was placed on a tee (height 15 cm) positioned on the table (height 72 cm). The seat of the chair was 65 cm from the ground. This arrangement meant that only the child's anatomy limited the possible vertical spatial errors above the ball but that the children could only hit 11 cm below the ball before they hit the table.

PROCEDURE

After an explanation and demonstration of the task, the children were seated in the primary position for each trial and asked to hold out their unseen right hand into which the experimenter placed the bat. The children were not told that different bats would be used. Children were allowed to

choose the starting position of the bat; this ranged from 25 to 36 cm from the ball in the coronal plane. Each experiment consisted of 18 trials (six swings with each of the three bats). The order of bat presentation was randomized for the first child and the same order was then used for all of the children to allow for direct comparison of the horizontal error on a trial-by-trial basis. On the command 'go', the children attempted to hit the ball. It was made clear to the children that the time they took to perform each trial was not being measured and that they should concentrate on hitting the ball.

The bat was hidden from sight by a cloth screen placed around the child's neck (Fig. 1). This was held horizontally by a frame which ensured that the material did not interfere with the children's back swing or the data recording. The children were sat in a chair and the occluding material was adjusted to ensure that only the ball was visible to the participant. The base of the chair was fixed to the floor but the seat was allowed to rotate around its vertical axis, allowing the children to move their bodies in a natural striking action. During the time that the bat passed through the target area it would have been possible for the children to see the bat. In practice, the speed with which all of the children hit the ball meant that the bat remained effectively unseen throughout the whole experiment. Each bat had an IRED marker

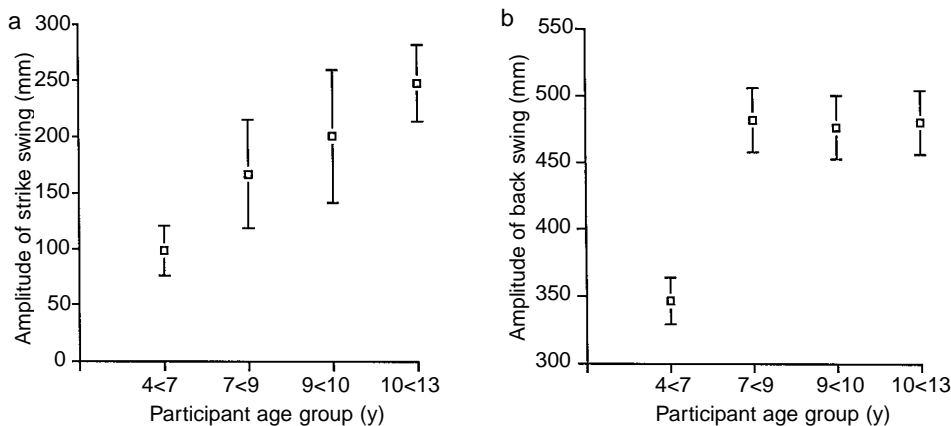


Figure 3: (a) Amplitude of back swing plotted as a function of age. Four different age bands plotted along ordinate and mean amplitude of back swing is plotted along abscissa. (b) Amplitude of strike swing plotted as a function of age.

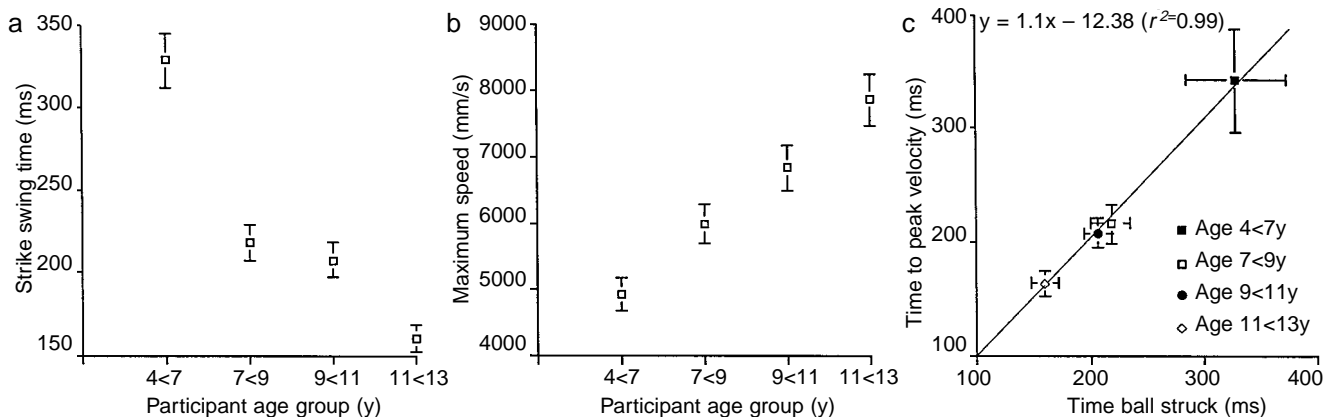


Figure 4: (a) Measure of time from initiation of strike swing to point where maximum tangential speed was reached, plotted as function of age. (b) Maximum tangential speed plotted as function of age. (c) Time to maximum tangential speed plotted as function of when ball was struck for each participant group.

attached to the centre point of the head.

Hitting the ball exactly in the centre of the bat is beneficial for the child as this reduces the jarring caused by hitting at a point other than the centre of percussion (Enoka 1994). Contact with the centre of the bat will also reduce the rotational force generated by hitting below or above the bat's longitudinal centre of rotation. Consequently, there were a number of factors within the experiment that made it advantageous to strike the ball with minimal endpoint spatial error while allowing the children to succeed at the task if errors were made.

DATA ANALYSIS

All of the data were analysed using a customized Labview™ (National Instruments Corporation, Texas, USA) programme. The data were filtered by a dual pass through a Butterworth second-order digital filter (low pass cut off at 20 Hz). Three components of the data were considered: kinematics of the whole movement, relative smoothness of the strike swing, and spatial accuracy of the strike swing. Spatial error was defined as the horizontal and vertical displacement of the bat centre with respect to the ball at the time of contact. The variable error represents the mean of the individual's standard

Table I: Constant and absolute vertical error with participants grouped according bat with which least horizontal error (mm) was made.

	Bat 1	Bat 2	Bat 3	Age band
Bat 1	2.3	-23.9	-51.9	3
Bat 2	57.5	5.6	-29.9	1
	20.7	-1.3	-7.5	1
	24.5	-22.1	-35.3	1
	42.6	11.1	-34.8	2
	58.3	2.4	-30.6	2
	22.0	-7.1	-57.1	2
	40.0	8.2	-28.8	2
	39.2	14.6	-22.5	2
	22.1	2.9	-35.7	2
	45.7	4.7	-31.3	3
	48.6	-7.5	-47.8	3
	37.8	2.4	-45.3	3
	30.1	1.8	-47.9	4
Mean (SD) signed	37.6 (3.5)	1.2 (2.5)	-35.0 (3.4)	
Mean (SD) unsigned	37.6 (3.5)	7.1 (1.6)	35.0 (3.4)	
Bat 3	91.5	30.6	22.1	1
	65.0	32.7	8.3	1
	64.4	26.4	-15.5	1
	50.6	24.4	6.3	1
	46.9	21.8	-13.5	2
	45.5	56.9	12.6	3
	39.6	14.8	-4.1	3
	41.0	51.9	3.7	3
	60.2	59.5	21.4	4
	38.9	26.7	4.9	4
	91.5	46.8	-7.8	4
	64.1	61.4	6.4	4
	50.5	42.7	1.1	4
	63.1	50.7	-5.5	4
Mean(SD) signed	58.1 (4.4)	39.1 (4.0)	2.9 (3.0)	
Mean (SD) unsigned	58.1 (4.4)	39.1 (4.0)	9.5 (1.7)	

Signed, mean calculated with positive values only.
 Unsigned, mean calculated with positive and negative values.

deviation scores (each individual's variability with the three bats). A normalized jerk measure was used to provide an indication of the 'smoothness' of the movement (Hogan 1984). The integrated squared jerk was normalized to provide a dimensionless measure of smoothness independent of movement duration or amplitude (Kitazawa et al. 1993, Teulings et al. 1996). Data were analysed using analysis of variance with Fisher protected least square difference posthoc comparisons. Log transformations were carried out before inferential analysis on data where the variance was proportional to the mean. Discussion of the results is restricted to the statistically reliable comparisons.

Results

KINEMATICS

Initial statistical analyses showed no relation between bat length and any of the kinematic measures. Therefore, these data were considered together. Figure 2 shows the velocity profiles obtained for a 12- and 6-year-old child, outlining many of the essential differences in the striking action

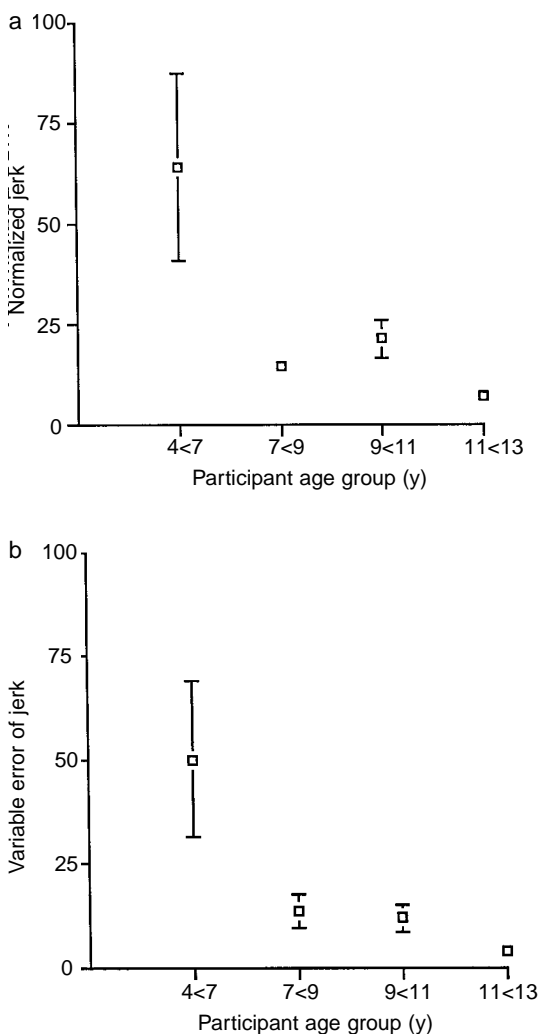


Figure 5: (a) Normalized jerk as function of age. Four different age bands plotted along ordinate and normalized jerk values plotted along abscissa. (b) Variable error (mean, SD) of jerk plotted as function of age band.

between the youngest and oldest groups of children. ANOVA on the means of interest showed a reliable effect of age on the amplitude of the back swing ($F[3,24]=4.366, p<0.02$). Contrasts showed that the youngest children had a smaller back swing than the two groups of older children (Fig. 3a). ANOVA on the means of interest showed a reliable effect of age on the amplitude of the strike swing $F(3,24)=3.616, p<0.03$ (Fig. 3c). Contrasts showed that the youngest children had a smaller strike swing than all of the older children. No reliable differences were found between the three oldest age groups.

As the participants' ages increased, the length of time of the strike swing decreased (Fig. 4a), and the maximum speed was achieved in a shorter period of time (Fig. 4b). ANOVA approached significance for the comparison between age and the time the ball was struck ($F[3,24]=2.984, p<0.052$) and was significantly different for the time to peak speed

($F[3,24]=3.447, p<0.04$). Contrasts showed that the youngest children swung the bat for a longer period of time and achieved peak speed later than the oldest children. ANOVA of the maximum tangential speed indicated a reliable main effect for age ($F[3,24]=3.957, p<0.02$), with the youngest children swinging more slowly than the two older groups of children and the children from age band 2 swinging more slowly than the oldest children.

To illustrate the relation between the time that the ball was struck and the time that peak velocity was achieved, these two measures were plotted as a function of one another. Figure 4c shows that all participants reached peak velocity close to when the ball was struck. The relation was described by the following equation: $y=1.1x-12.38$ ($r^2=0.99$) where y is maximum velocity and x is the time at which the ball was struck, indicating that the participants achieved maximum velocity just slightly after striking the ball.

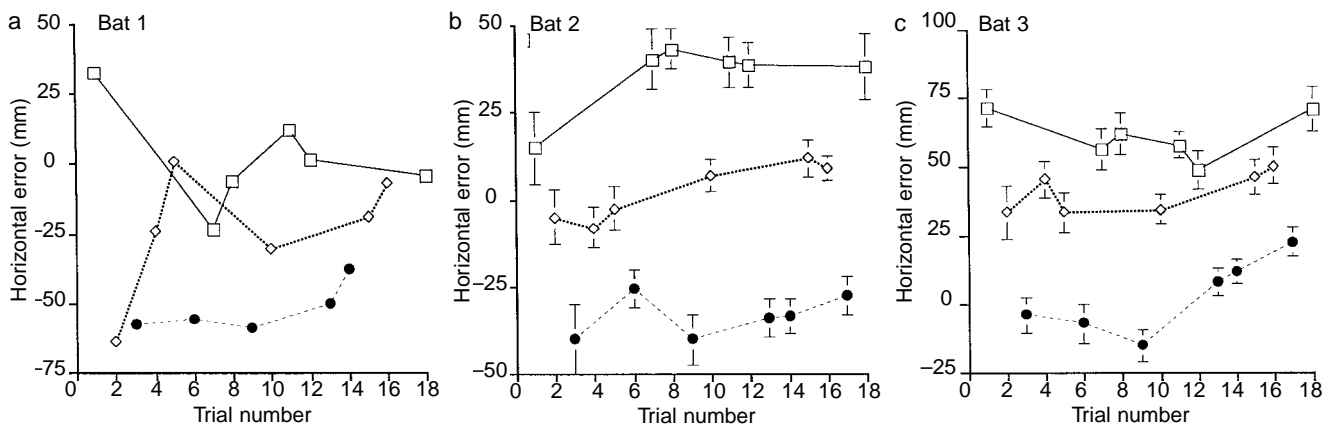


Figure 6: Change in horizontal error plotted as function of trial number for each three bat lengths averaged across participants who made least error with (a) smallest bat ($n=14$), (b) middle bat ($n=13$), (c) longest bat ($n=1$). \square bat 1, \diamond bat 2, \bullet bat 3.

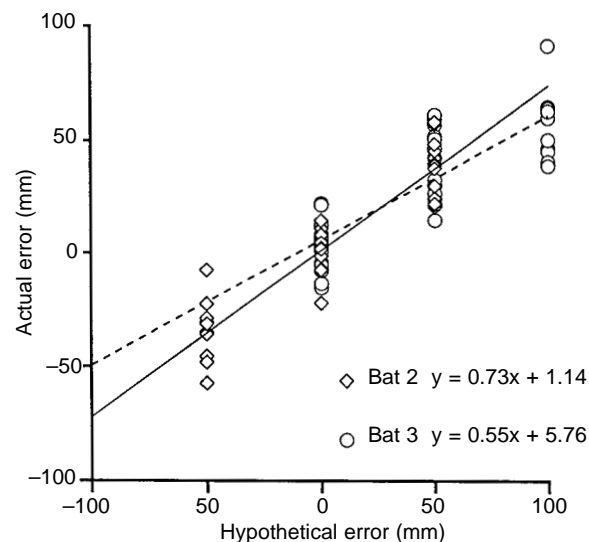


Figure 7: Horizontal constant error expressed as function of hypothetical horizontal error. Data from the child who made the least error with bat 1 omitted for clarity ($y = 2.6 + 0.54x, r^2 = 1.0$). See text for definition of hypothetical error.

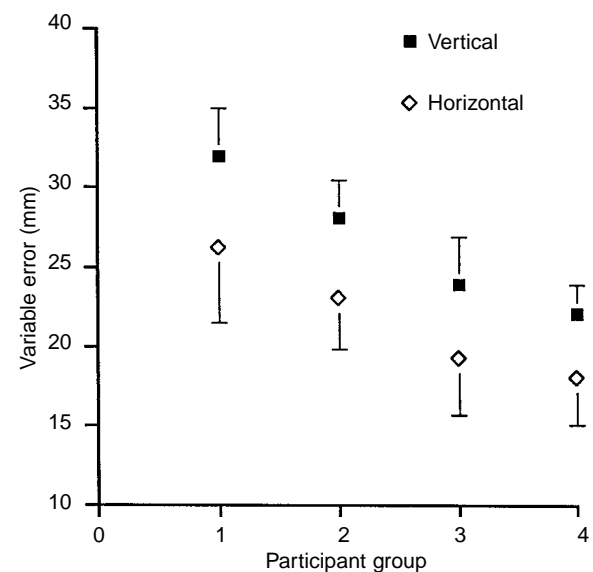


Figure 8: Vertical and horizontal variable error as a function of age.

ANOVA of the normalized jerk scores indicated that the older children were able to produce a swing that was consistently smoother (reliable main effect for age $F[3,22]=4.381$, $p<0.02$) while the youngest children were less smooth than both the next oldest group (age band 2) and the oldest children (Fig. 5a). ANOVA of the variable error of the normalized jerk showed a reliable main effect for age ($F[3,24]=6.018$, $p<0.004$). The youngest children had the greatest variable error: this variable error was reliably different from the other three groups (Fig. 5b).

SPATIAL ACCURACY

No statistically reliable relation was found between age and horizontal error. Inspection of the data showed that, regardless of age, each child was more accurate with one of the bats. The children were, therefore, divided into groups determined by the bat with which they made the smallest average horizontal constant error across all the trials. It was found that 14 children minimized the horizontal error for bat 3, 13 children minimized the horizontal error for bat 2, and one child minimized the horizontal error for bat 1 (Table 1). Figure 6 plots the horizontal constant error averaged across participants as a function of the trial number. These figures suggest that the children learned the length of the bat with which they first made an horizontally accurate strike. Figure 7 shows the relation between the actual horizontal error and the error predicted under the assumption that the child did not use kinaesthetic information to adjust their strike. The regression equation for this function is $y = 0.63x + 1.8$ ($r^2=0.84$) where y is the actual horizontal error and x is the hypothetical error. This result suggests that the children do make some adjustment for the different bat lengths. To examine the spatial consistency with which the children hit the ball, the variable error (mean standard deviation) was examined. A decrease in variability was found for both the horizontal and vertical spatial error as the age of the group increased (Fig. 8) suggesting that the older children were more consistent in where they struck.

Discussion

KINAESTHETIC JUDGEMENTS

This study used a striking task to explore how well young children could make kinaesthetic judgements. All of the children produced almost perfect horizontal accuracy with one of the bats (and close to perfect vertical accuracy with all of the bats), suggesting that they were able to access the kinaesthetic information required for task success. On the other hand, all of the children made horizontal errors with two of the bats: notably these errors were in a direction predicted by the bat with which they made the least error. This result can be explained by the children building a representation of a particular bat during the initial stages of the experiment (i.e. learning bat length). It appears as if the children learned the length of only one bat and then failed to use fully the available kinaesthetic information when striking with the other two bats. Such information would have indicated that the other two bats were of different lengths (see Fig. 7).

If we accept that the children have learned a single bat length, the question arises as to why they selected a particular bat. At the beginning of the experiment the children must have used kinaesthetic information to gauge the length of the bats. The children's success in using this information is

evidenced by the fact that all of the children had made a 'clean' strike within three trials (see Fig. 6) and it appears that the children learned the length of the bat with which they first made such a strike. It is notable that even 4-year-old children were able to meet the accuracy constraints of the experimental task. This finding may be compared to those from a number of other studies that have reported a reduced ability to make 'kinaesthetic judgements' in children of this age (e.g. Bairstow and Laszlo 1981, Lord and Hulme 1987, Elliott et al. 1988). It seems clear that the ability of children to make judgements relating to the perception of limb position is closely related to the method of assessment employed. The evidence from the present study suggests that the findings of reduced kinaesthetic sensitivity in earlier studies may be due to factors other than an inaccuracy in the perception of sensed limb position (for example, comprehension of the task, memory constraints, etc.). The only spatial measure which did show a change with the age of the group was the variable error. In both the vertical and the horizontal dimension, the older children showed a lower degree of spatial variability. This suggests that all of the children adopted a similar successful strategy but that the older children were better able to produce movement of the desired accuracy consistently (see Fig. 8).

REFINEMENT OF THE STRIKING ACTION

Most of the measures used to describe the striking showed a clear developmental trend with the older groups of children performing the movement in a quantitatively different manner to the younger groups. For example, the older groups swung the bat through a greater amplitude when drawing back and when striking forwards (see Fig. 3). The older groups of children also had a shorter performance time for the striking movement and a greater peak speed during the strike (see Fig. 4).

The study was successful in plotting some changes in the striking action as a function of age. It was found that young children both produced a movement pattern that was less smooth than the older children and demonstrated a greater degree of variability in the smoothness of the movements. As individuals, the youngest group of children were also less consistent in their smoothness scores: on some strikes the youngest children produced relatively smooth movements but other trials were characterized by 'jerky' performance. It seems reasonable to suggest that the nervous system learns the motor commands associated with the smooth movements and attaches a higher weighting to these commands on subsequent movements, ultimately leading to a refinement of the action.

Conclusion

This article has provided a preliminary exploration of the striking action in children of different ages. The results provide a useful insight into the use of kinaesthetic information in young children. Notably, our findings indicate a higher level of kinaesthetic sensitivity than is typically reported in studies using static limb positioning tasks (see Smyth and Mason 1999 for a useful review). This finding suggests that the striking task might be a useful tool for exploring kinaesthetic function in children with movement problems; kinaesthetic deficits have been reported frequently in movement disorders as was stated at the beginning of this paper.

Although we did not observe age differences in spatial accuracy, we did find that older children performed the strike movement in a quantitatively different manner to younger children. In particular, our results clearly indicate a developmental trend towards movements which approach optimal smoothness. It appears that the striking action becomes more refined with age and the increased smoothness provides an index of this refinement. This finding suggests that the striking task might be used to dissect the poor refinement of particular movement skills in children with developmental disorders and supports our contention that the striking task has potential diagnostic value.

Accepted for publication 28 January 2000.

References

- Bairstow PJ, Laszlo JI. (1981) Kinaesthetic sensitivity to passive movements and its relationship to motor development and motor control. *Developmental Medicine & Child Neurology* **23**: 606–16.
- Barac-Cikoja D, Turvey MT. (1991) Perceiving aperture size by striking. *Journal of Experimental Psychology: Human Perception and Performance* **17**: 330–46.
- Burton G, Turvey MT, Solomon HY. (1990) Can shape be perceived by dynamic touch? *Perception and Psychophysics* **48**: 477–87.
- (1991) Attentionally splitting the mass distribution of hand-held rods. *Perception and Psychophysics* **50**: 129–40.
- Doyle AJR, Elliott JM, Connolly KJ. (1986) Measurement of kinaesthetic sensitivity. *Developmental Medicine & Child Neurology* **28**: 188–93.
- Elliott JM, Connolly KJ, Doyle AJR. (1988) Development of kinaesthetic sensitivity and motor performance in children. *Developmental Medicine & Child Neurology* **30**: 80–92.
- Enoka R. (1994) *Neuromechanical Basis of Kinesiology*. Champaign, IL: Human Kinetics.
- Flash T. (1987) The control of hand equilibrium trajectories in multi-joint arm movements. *Biological Cybernetics* **57**: 257–74.
- Hogan N. (1985) The coordination of arm movements: an experimentally confirmed mathematical model. *Journal of Neuroscience* **5**: 1688–703.
- Henderson SE, Sugden DA. (1992) *Movement Assessment Battery for Children*. New York: Psychological Corporation.
- Hoare D, Larkin D. (1991) Kinaesthetic abilities of clumsy children. *Developmental Medicine & Child Neurology* **33**: 671–8.
- Hogan N. (1984) An organising principle for a class of voluntary movements. *Journal of Neuroscience* **4**: 2745–54.
- Keogh J, Sugden D. (1985) *Movement Skill Development*. New York: Macmillan.
- Kitazawa S, Goto T, Urushihara Y. (1993) Quantitative evaluation of reaching movements in cats with and without cerebellar lesions using normalised integral of jerk. In: Mano N, Hamada I, Delong MR, editors. *Role of the Cerebellum and Basal Ganglia in Voluntary Movement*. Amsterdam: Elsevier. p 11–19.
- Laszlo JI, Bairstow PJ. (1983) Kinaesthesia: its measurement, training and relationship to motor control. *Quarterly Journal of Experimental Psychology* **35**: 411–21.
- (1985) *Perceptual-Motor Behaviour: Development Assessment and Therapy*. New York: Praeger.
- (1988) Kinaesthetic Sensitivity of normal and clumsy children: a reply to Lord and Hulme. *Developmental Medicine & Child Neurology* **30**: 686–8.
- Lord R, Hulme C. (1987) Kinaesthetic sensitivity of normal and clumsy children. *Developmental Medicine & Child Neurology* **29**: 720–5.
- Mon-Williams M, Wann JP, Pascal E. (1999) The integrity of visual-proprioceptive mapping in developmental coordination disorder. *Developmental Medicine & Child Neurology* **41**: 247–54.
- Nelson W. (1983) Physical principles for economies of skilled movements. *Biological Cybernetics* **46**: 135–47.
- Smyth MM, Mason UC. (1998) Direction of response in aiming to visual and proprioceptive targets in children with and without Developmental Co-ordination Disorder. *Human Movement Science* **17**: 515–39.
- Teulings HL, Contreras-Vidal JL, Stelmach GE, Adler CH. (1996) Parkinsonian coordination impairments of fingers, wrist and arm in fine motor control. *Experimental Neurology* **146**: 159–70.
- Turvey M, Burton G, Pagano C, Solomon H, Runeson S. (1992) Role of the inertia tensor in perceiving object orientation by dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance* **18**: 714–27.
- Turvey MT. (1996) Dynamic Touch. *American Psychologist* **51**: 1134–52.
- Von Hofsten C, Rösblad B. (1988) The integration of sensory information in the development of precise manual pointing. *Neuropsychologia* **26**: 805–21.
- Wann JP. (1987) Trends in the refinement and optimisation of fine-motor trajectories: observations from an analysis of the handwriting of primary school children. *Journal of Motor Behaviour* **19**: 13–37.
- (1991) The integrity of visual-proprioceptive mapping in cerebral palsy. *Neuropsychologia* **29**: 1095–106.
- Jones J. (1986) Space-time invariance in handwriting: Contrasts between primary school children displaying advanced or retarded handwriting acquisition. *Human Movement Science* **5**: 275–96.
- Nimmo-Smith I, Wing AM. (1989). Why are strategies sensitive? Smoothing the way for a raison d'être. *Behavioural and Brain Sciences* **12**: 235–6.
- Mon-Williams M, Carson RG. (1998) Assessing manual control in children with coordination difficulties. In: Connolly K, editor. *The Psychobiology of the Hand*. Cambridge: Cambridge University Press. p 213–29.